Organic Waste Recycling

Technology and Management

3rd Edition

Chongrak Polprasert

IWA Publishing

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Preface

As the world population is projected to increase from the current number of 6 billions to 9 billions in the year 2050, the amount of organic wastes generated from human, animal and agricultural activities would also increase, causing more pollution problems to the environment. The Millennium Development Goals call for actions on environmental protection, sustainable development and poverty alleviation. Despite a lot of efforts from the national and international agencies, waste treatment alone will not be able to respond effectively to the challenges.

The book presents new concept and strategy of waste management which combines technologies of waste treatment and recycling and emphasizing the benefits to be gained from use of the recycled products. These technologies such as composting, fermentation, algal photosynthesis, and natural treatment systems are cost-effective, bring economic returns and are applicable to most countries, in particular those located in the tropical areas. They are considered as sustainable technologies which, if properly applied, should be an effective tool in responding to the Millennium Development Goals.

In the third edition, I have included up-to-date information on organic waste recycling technologies and more case studies of successful organic waste recycling programs implemented in several countries. New sections on: cleaner production is added in chapter 2, ethanol production in chapter 4, chitin and chitosan production in chapter 6, and constructed wetlands in chapter 7. Chapter 10 has been revised to cover management aspects of organic waste recycling programs including the planning, institutional development and regulatory standards. More examples and exercises are given in each chapter to help the readers understand the technical principles and their application.

This book is intended to be used as a text for students majoring in environmental sciences and engineering and for graduate students conducting research in the related fields. Many universities worldwide have developed new curricula on environment and sustainable development or are offering specialized courses on sustainable waste management, all relating to the subject contents of this book. Environmental professionals and policy makers should find this book a useful reference source for planning, design and operation of organic waste recycling programs.

In the preparation of the third edition, I am grateful to my graduate students at the Asian Institute of Technology, Bangkok, Thailand and the UNESCO-IHE Institute for Water Education, Delft, the Netherlands, for the constructive suggestions on the book contents and feedbacks on the use of the book in teaching and application of these organic waste recycling technologies in their home countries. The book reviewers, Professor Dr. Hubert Gijzen, Director and Representative of UNESCO office, Jakarta, Indonesia and Dr. Rao Surampalli, Engineer Director of U.S. Environmental Protection Agency, Kansas, U.S.A. and adjunct Professor of Environmental Engineering at the University of Nebraska, U.S.A., gave useful and constructive suggestions on the content of the revised book. I am thankful to Professor Dr. Shigeo Fujii who invited me to spend a sabbatical leave at the Reseach Center for Environmental Quality Management, Kyoto University, Japan, which allowed me to finalize the book revision. My student assistants, Warounsak Liamleam and Robert Dongol, did an excellent job in assisting me in the overall revision of the book.

I would like to express my sincere appreciation to the Aeon Group Environment Foundation, Japan, for the generous support of the endowed professorial chair which has enabled me to complete the revision of this book. Grateful acknowledgement is expressed to Alan Click of IWA Publishing, London, for his professional support in the publication of the third edition. The inspiration and encouragement I always receive from Nantana, Jim and Jeed made this project possible.

Chongrak Polprasert
Bangkok, Thailand
January 2007

Abbreviations and symbols

AFP	advanced facultative ponds
AIT	Asian Institute of Technology, Bangkok, Thailand
AIWPS	advanced integrated wastewater pond system
AMP	advanced maturation ponds
APU	aquatic processing unit
ASP	advanced settling ponds
atm	atmosphere (pressure)
AU	animal unit
BARC	Beltsville aerated rapid composting
BOD_5	5-day biochemical oxygen demand
BOD_L	ultimate biochemical oxygen demand
BTU	British thermal unit
C	carbon
C/N	carbon/nitrogen ratio
C_2H_5OH	ethanol
cal	calorie

CEC	cation exchange capacity
CH_3OH	methanol
CH_4	methane gas
Cl	chloride
cm	centimeter
CO	carbon monoxide
CO_2	carbon dioxide
COD	chemical oxygen demand
CP	cleaner production
d	days
d	dispersion number
DAF	dissolved air flotation
DDT	dichloro-diphenyl-trichloro-ethane, $(ClC_6H_4)_2CHCCl_3$
DO	dissolved oxygen
DO_d	dissolved oxygen at dawn
e or exp	exponential
EC	electrical conductivity
FAO	United Nations Food and Agriculture Organization
FCR	food conversion ratio
FFB	fresh fruit bunches (referring to palm oil wastewater)
ft	foot
FWS	free water surface (constructed wetlands)
g	gram
gal	gallon
gcal	calorie
gmole	molecular weight in grams of any particulat compound
H	hydrogen
h	unit heat of algae
H_2	hydrogen gas
H_2S	hydrogen sulfide gas
ha	hectare
hp	horsepower
hr	hour
HRAP	high-rate algal pond
HRT	hydraulic retention time
in	inch
IRCWD	International Reference Centre for Waste Disposal, Switzerland
ISO	International standards organization
K	potassium
kcal	kilocalorie

kg	kilogram
kJ	kilojoule
km	kilometer
KVIC	Khadi and Village Industries Commission (India)
kWh	kilowatt-hour
L	liter
LAS	linear alkylbenzene sulfonates
lb	pound
LDP	limiting design parameter
LPG	liquefied petroleum gas
m	meter
meq	milli-equivalent (referring to concentration of an ion)
mg	milligram
mgad	million gallons per acre per day
mgd	million gallons per day
min	minute
mL	milliliter
mM	milliMolar
mm	millimeter
MPN	most probable number
mV	millivolt
MWh	megawatt-hour
N	nitrogen
NAS	U.S. National Academy of Sciences
NH_3	un-ionized ammonia
NH_3-N	ammonia N
NH_4^+-N	ammonium N
nm	nanometer = 10^{-9} m
NO_2^-	nitrite
NO_3^-	nitrate
NO_x	nitrogen oxides in various oxidation states
O	oxygen
OF	overland flow process (referring to land treatment)
Org-N	organic nitrogen
P	phosphorus
PCBs	polychlorinated biphenyls
PFU	plaque forming unit
P_a	algal productivity
PO_4^{3-}	phosphate
ppm	part per million

psi	pound per square inch
psi	pound per square inch (referring to pressure)
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act of the U.S.A.
RI	rapid infiltration process (referring to land treatment)
RMP	red mud plastic
rpm	revolution per minute
s or sec	second
S	sulfur
SAR	sodium adsorption ratio
SD	stocking density (of fish or aquatic weeds)
SF	subsurface flow (constructed wetlands)
SI	international system
SO_x	sulfur oxides in various oxidation states
SR	slow rate (irrigation) process (referring to land treatment)
SS	suspended solids
TKN	total Kjeldahl nitrogen = organic N + NH_4^+-N + NH_3-N
TLW	total live weight of animal
TN	total nitrogen
TOC	total organic carbon
ton	metric tonne = 1000 kg
TP	total phosphorus
TS	total solids
TSS	total suspended solids
TVS	total volatile solids
TWW	total wet weight
U.N.	United Nations
U.S. DA	United States Department of Agriculture
U.S. EPA	United States Environmental Protection Agency
UASB	upflow anaerobic sludge blanket digester
UMER	unit mass emission rate (referring to tapioca starch wastewater)
UNEP	United Nations Environment Program
UNESCO	United Nations Eduction, Science and Culture Organization
UV	ultraviolet
VIP	ventilated improved pit
VSS	volatile suspended solids
W	Watt
WHO	World Health Organization
WHP	water hyacinth ponds
wk	week

WSP	waste stabilization ponds
yr	year
z	pond depth or distance down slope (in case of OF)
γ	porosity of media
θ_C	mean cell residence time
µg	microgram = 10^{-6} gram
µm	micrometer
°C	degree centigrade (temperature)
°F	degree Fahrenheit (temperature)
%	percent

Atomic weight and number of elements

Element	Symbol	Atomic number	Atomic weight
Aluminum	Al	13	26.97
Antimony	Sb	51	121.76
Argon	A	18	39.944
Arsenic	As	33	74.91
Barium	Ba	56	137.36
Beryllium	Be	4	9.02
Bismuth	Bi	83	209.00
Boron	B	5	10.82
Bromine	Br	35	79.916
Cadmium	Cd	48	112.41
Calcium	Ca	20	40.08

Element	Symbol	Atomic number	Atomic weight
Carbon	C	6	12.01
Cerium	Ce	58	140.13
Cesium	Cs	55	132.91
Chlorine	Cl	17	35.457
Chromium	Cr	24	52.01
Cobalt	Co	27	58.94
Copper	Cu	29	63.57
Dysprosium	Dy	66	162.46
Erbium	Er	68	167.2
Europium	Eu	63	152.0
Fluorine	F	9	19.00
Gadolinium	Cd	64	156.9
Gallium	Ga	31	69.72
Germanium	Ce	32	72.60
Gold	Au	79	197.2
Hafnium	Hf	72	178.6
Helium	He	2	4.003
Holmium	Ho	67	164.94
Hydrogen	H	1	1.0081
Indium	In	49	114.76
lodine	I	53	126.92
Iridium	Ir	77	193.1
Iron	Fe	26	55.84
Krypton	Kr	36	83.7
Lanthanum	La	57	138.92
Lead	Pb	82	207.21
Lithium	Li	3	6.940
Lutecium	Lu	71	175.00
Magnesium	Mg	12	24.32
Manganese	Mn	25	54.93
Mercury	Hg	80	200.61
Molybdenum	Mo	42	95.95
Neodymium	Nd	60	144.27
Neon	Ne	10	20.183
Nickel	Ni	28	58.69
Niobium	Nb	41	92.91
Nitrogen	N	7	14.008
Osmium	Os	76	190.2
Oxygen	O	8	16.000

Element	Symbol	Atomic number	Atomic weight
Palladium	Pd	46	106.7
Phosphorus	P	15	30.98
Platinum	Pt	78	195.23
Potassium	K	19	39.096
Praseodymium	Pr	59	140.92
Protactinium	Pa	91	231
Radium	Ra	88	226.05
Radon	Rn	86	222
Rhenium	Re	75	186.31
Rhodium	Rh	45	102.91
Rubidium	Rb	37	85.48
Ruthenium	Ru	44	101.7
Samarium	Sm	62	150.43
Scandium	Sc	21	45.10
Selenium	Se	34	78.96
Silicon	Si	14	28.06
Silver	Ag	47	107.880
Sodium	Na	11	22.997
Strontium	Sr	38	87.63
Sulfur	S	16	32.06
Tantalum	Ta	73	180.88
Tellurium	Te	52	127.61
Terbium	Tb	65	159.2
Thallium	Tl	81	204.39
Thorium	Th	90	232.1
Thulium	Tm	69	169.4
Tin	Sn	50	118.70
Titanium	Ti	22	47.90
Tungsten	W	74	183.92
Uranium	U	92	238.07
Vanadium	V	23	50.95
Xenon	Xe	54	131.3
Ytterbium	Yb	70	173.04
Yttrium	Y	39	88.92
Zinc	Zn	30	65.38
Zirconium	Zr	40	91.22

Source: www.petrik.com

Conversion factors for SI units

Measurement	Unit	Multiplier	SI unit
Area	in^2	6.452	cm^2
	ft^2	0.0929	m^2
	yd^2	0.836	m^2
	acre	0.4047	ha
	acre	4047	m^2
Flow	ft^3/s	0.02832	m^3/s
	gal/min	0.0631	L/s
	gal/d	$4.4x10^{-5}$	L/s
		0.044	m^3/s
	mgd	43.81	L/s
	ft^3/m	0.4720	L/s
Heat	Btu	1.055	kJ
	Btu	2.928×10^{-4}	kWh
	Btu	0.2520	kcal
	hp	745.7	watt

Measurement	Unit	Multiplier	SI unit
Heat	hp	10.70	kcal/min
Length	in	2.54	cm
	in	25.40	mm
	ft	30.48	cm
	ft	0.3048	m
	yd	0.914	m
	mile	1.605	km
Load/Pressure	lb/ft^2	4.881	kg/m^2
	atmosphere	10,333	kg/m^2
	lb/in^2	703	kg/m^2
Mass	lb	0.4536	kg
Temperature	°F	(°F - 32)/1.8	°C

1

Introduction

1.1 PROBLEMS AND NEED FOR WASTE RECYCLING

A significant challenge confronting engineers and scientists in developing countries is the search for appropriate solutions to the collection, treatment, and disposal or reuse of domestic waste. Technologies of waste collection and treatment that have been taught to civil engineering students and practiced by professional engineers for decades are, respectively, the water-borne sewerage and conventional waste treatment systems such as activated sludge and trickling filter processes. However, the above systems do not appear to be applicable or effective in solving the sanitation and water pollution problems in developing countries. Supporting evidence for the above statement is the result of a World Health Organization report (WHO 2000) which showed that in the year 2000 some 1.1 billion people (about 18% of the world population) did not have access to improved water supply, and 2.4 billions (about 40% of the world population) were without access to any sort of improved sanitation facility. For both the water supply and sanitation services, the vast majority of those without access are in Asia (as shown in Table

1.1). Although the percentages of population served with adequate water supply and sanitation increased during the past decade, due to rapid population and urban growth, these percentages for the urban areas are not expected to increase much in the next decade, while a lot of improvement is needed for the rural areas.

Table 1.1 Water supply and sanitation coverage (adapted from United Nations 2005)

Regions	**Percentage covered in year**	
	1990	**2002**
Developing		
Urban water	93	92
Rural water	59	70
Total water	71	79
Urban sanitation	68	73
Rural sanitation	16	31
Total sanitation	34	49
Global		
Urban water	95	95
Rural water	63	72
Total water	77	83
Urban sanitation	79	81
Rural sanitation	25	37
Total sanitation	49	58

Sanitation conditions in both urban and rural areas need to be much improved as large percentages of the population still and will lack these facilities (Table 1.1). There are approximately 3.6 million deaths and 5.7 billion episodes of morbidity per year related to poor quality of water supply and unhygienic sanitation (WHO 2000). One of the U.N. Millenium Development Goals is to have water and sanitation for all by the year 2025, with the interim target of halving the proportion of people living in extreme poverty or those without adequate water supply and sanitation by 2015. To meet the 2025 target, with continued population growth (Figure 1.1), some 2.9 billion people will need to be provided with improved water supply and about 4.2 billion people will need improved sanitation.

Polprasert and Edwards (1981) cited several reasons for the failure to provide sewerage to the population of the cities of the developing countries. The construction of sewerage systems implies large civil engineering projects with high investment costs. These projects are ill-suited to incremental implementation in densely built-up cities and usually involve long planning periods, which can take up to a decade to implement. In the mean time, the problem has once more outstripped the solution.

Conventional waste treatment is rarely linked to waste reuse, such as irrigation, fertilization, or aquaculture. Thus it does not generate either income or employment, both high priorities in developing countries.

Most obviously, sewers are simply too expensive. The cost of sewers and sewage treatment is high by the standards of the richest countries in the world. Not only are many of the cities in the developing countries larger, but an unprecedented number of people must be provided with hygienic sanitation in an extremely short time. The developed countries had the luxury of almost a century to build their sanitation systems, the developing countries must do it in a decade, on a larger scale, often with water shortages, in extremely densely populated cities, and sometimes with a lower level of technological development than existed in Europe and North America at the turn of the century. And this must be done at a cost that is affordable today.

Bangkok city, the capital of Thailand, is a typical case study to show the difficulty of implementing sewerage scheme in a newly industrialized country. In Bangkok, excreta disposal is generally by septic tank or cesspool; other wastewaters from kitchens, laundries, bathrooms, etc. (grey water) are discharged directly into nearby storm drains or canals. Because the Bangkok subsoil is impermeable clay, overflows from septic tanks and cesspools normally find their ways into the canals and storm drains, resulting in serious water pollution and health hazard to the people. A master plan of sewerage, drainage and flood protection for Bangkok city was completed in 1968; the required facilities to serve approximately 1.5 million people would cost about US$110 million. By the year 2000, the entire program would serve about 6 million people at a cost in excess of US$500 million. The proportions of cost by facility were: sewerage 35 percent, drainage 27 percent, and flood protection 38 percent (Lawler and Cullivan 1972). Since the year 2006, seven central wastewater treatment plants, which employ primary and secondary treatment processes, are in operation and costing about US$ 500 million in construction. They are able to treat 40 % of the total wastewater volume or about 1 million cubic meters per day. The remaining wastewater, raw or partially treated, is being discharged into nearby storm drains or water bodies.

Besides the sanitation problem, man's energy needs have also grown exponentially, corresponding with human population growth and technological advancements (Figures 1.1 and 1.2). Although the energy needs are being met by the discovery of fossil fuel deposits, these deposits are limited in quantity and their associated costs of exploration and production to make them commercially available are high. Figure 1.2 shows the world fuel energy consumption to increase almost linearly since 1970 and is projected to be more than double in the year 2025. The worldwide energy crisis in the 1970s and very high oil prices in the 2000s are examples to remind us of the need for resources conservation and the need to develop alternative energy sources, e.g. through waste recycling.

Another concern for rapid population growth is the pressure exerted on our fixed arable land area on earth. Table 1.2 projects the ratio of arable land area over world population in the year 2063 to be half of that in the year 2000. There is an obvious need to either control population growth or produce more foods for human needs.

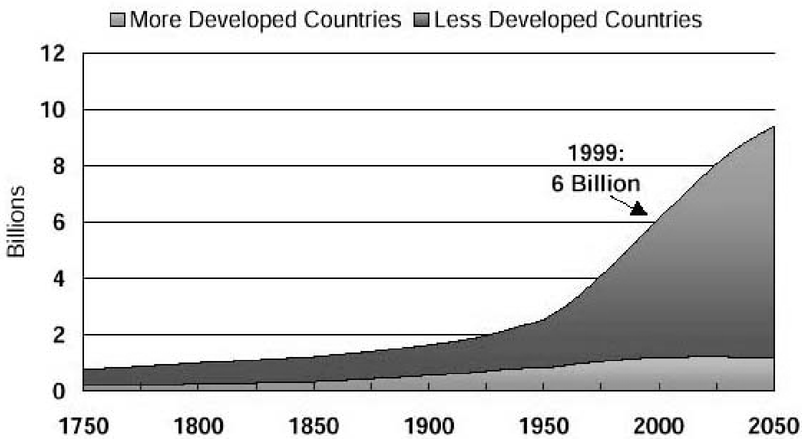

Figure 1.1 World population increases with human advances in science and technology (United Nations, 2005)

Table 1.2 Population growth and arable land

Year	Estimated population billion	Arable land ha/capita
2000	6	1
2020	10	0.6
2063	22	0.3
2100	?	0.1-0.2

Note: Earth total surface is 51 billion ha. Only 6 billion ha is arable land suitable for crop production (adapted from Oswald 1995)

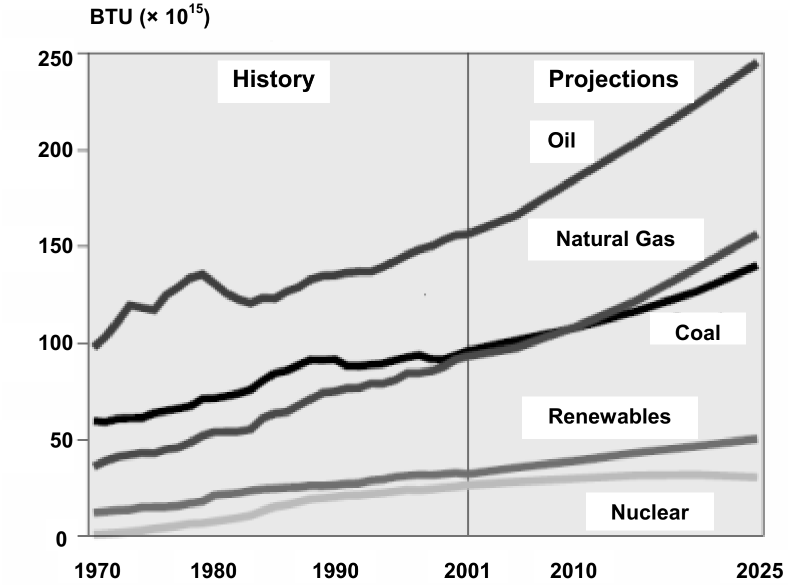

Figure 1.2 Energy consumption increases and changes in use pattern with human advances in science and technology (Energy Information Administration 2004)

Organic wastes such as human excreta, wastewater and animal wastes, contain energy which may be recovered by physical, chemical, and biological techniques, and combinations of these. Incineration and pyrolysis of sewage sludge are examples of physical and chemical methods of energy recovery from municipal and agricultural solid wastes; however, these methods involve very high investment and operation costs, which are not yet economically viable. The treatment and recycling of organic wastes can be most effectively accomplished by biological processes, employing the activities of microorganisms such as bacteria, algae, fungi, and other higher life forms. The by-products of these biological processes include compost fertilizer, biofuels, and protein biomass. Because the growth of organisms (or the efficiency of organic waste treatment/recycling) is temperature-dependent, areas having hot climates should be most favorable for implementation of the waste recycling schemes. However, waste recycling is applicable to temperate-zone areas also, with successful results from several projects (from which many design criteria were derived) presented in this book.

It is therefore evident that technologies of waste management which are simple, practical, and economical for use should be developed, and they should both safeguard public health and reduce environmental pollution. With the current energy crisis and since one of the greatest assets in tropical areas - where most developing countries are located - is the production of natural resources, the concept of waste recycling rather than simply waste treatment has received wide attention. A combination of waste treatment and recycling such as through biogas (methane) production, composting, or aquaculture, besides increasing energy or food production, will, if carried out properly, reduce pollution and disease transfer (Rybczynski *et al.* 1978). Waste recycling also brings about a financial return on the biogas, compost, and algae or fish which may be an incentive for the local people to be interested in the collection and handling of wastes in a sanitary manner.

The technologies to be discussed in this book apply mainly to human waste (i.e. excreta, sludge, nightsoil, or wastewater), animal wastes and agro-industrial wastewaters whose characteristics are organic in nature.

1.2 OBJECTIVES AND SCOPE OF ORGANIC WASTE RECYCLING

The objectives of organic waste recycling are to treat the wastes and to reclaim valuable substances present in the wastes for possible reuses. These valuable substances include carbon (C), nitrogen (N), phosphorus (P), and other trace elements present in the wastes. The characteristics and significance of these substances are described in Chapter 2.

The possible methods of organic waste recycling are as follows:

1.2.1 Agricultural reuses

Organic wastes can be applied to crops as fertilizers or soil conditioners. However, direct application of raw wastes containing organic forms of nutrients may not yield good results because crops normally take up the inorganic forms of nutrients such as nitrate (NO_3^-) and phosphate (PO_4^{3-}). Bacterial activities can be utilized to break down the complex organic compounds into simple organic and finally inorganic compounds. The technologies of composting and aerobic or anaerobic digestion are examples in which organic wastes are stabilized and converted into products suitable for reuse in agriculture. The use of untreated wastes is undesirable from a public health point of view because of the occupational hazard to those working on the land being fertilized, and the risk that contaminated products of the reuse system may subsequently infect man or other animals contacting or eating the products.

Wastewater that has been treated (e.g. by sedimentation and/or biological stabilization) can be applied to crops or grasslands through sprinkling or soil infiltration. The application of sludge to crops and forest lands has been practiced in many parts of the world.

1.2.2 Biofuels production

Organic wastes can be biochemically converted into biofuels such as biogas and ethanol which can be used for heating or as fuel for combustion engines and co-generators for electricity and heat generation.

Biogas, a by-product of anaerobic decomposition of organic matter, has been considered as an alternative source of energy. The process of anaerobic decomposition takes place in the absence of oxygen. The biogas consists mainly of methane (about 65 percent), carbon dioxide (about 30 percent), and trace amounts of ammonia, hydrogen sulfide, and other gases. The energy of biogas originates mainly from methane (CH_4) whose calorific value is 1,012 BTU/ft^3 (or 9,005 kcal/m^3) at 15.5 °C and 1 atmospheric pressure or 211 kcal/g molecular weight, equivalent to 13 kcal/g. The approximate calorific value of biogas is 500-700 BTU/ft^3 (4,450-6,230 kcal/m^3).

For small-scale biogas digesters (1-5 m^3 in size) situated at individual households or farm lands, the biogas produced is used basically for household cooking, heating and lighting. In large wastewater treatment plants, the biogas produced from anaerobic digestion of sludge is frequently used as fuel for boiler and internal combustion engines. Hot water from heating boilers may be used for digester heating and/or building heating. The combustion engines, fuelled by the biogas, can be used for wastewater pumping, and have other miscellaneous uses in the treatment plants or in the vicinity.

The slurry or effluent from biogas digesters, though still polluted, is rich in nutrients and is a valuable fertilizer. The normal practice is to dry the slurry, and subsequently spread it on land. It can be used as fertilizer to fish ponds, although little work has been conducted to date. There are potential health problems with biogas digesters in the handling and reuse of the slurry. It should be treated further; such as through prolonged drying or composting prior to being reused.

Ethanol or ethyl alcohol (C_2H_5OH) can be produced from three main types of organic materials such as: sugarcane and molasses (containing sugar); cassava, corn and potato (containing carbohydrates) and wood or agricultural residues (containing cellulose). Except those containing sugar, these organic materials need to be converted firstly into sugar, then fermented by yeast into ethanol, and finally distilled to remove water and other fermentation products from ethanol. The calorific value of ethanol is 7.13 kcal/g or 29.26 kJoule/g.

1.2.3 Aquacultural reuses

Three main types of aquacultural reuses of organic wastes in hot climates involve the production of micro-algae (single-cell protein), aquatic macrophytes, and fish. Micro-algal production normally utilizes wastewater in high-rate photosynthetic ponds. Although the algal cells produced during wastewater treatment contain about 50 percent protein, their small size, generally less than 10 μm has caused some difficulties for the available harvesting techniques which as yet are not economically viable. Aquatic macrophytes such as duckweeds, water lettuce or water hyacinth grow well in polluted waters and, after harvesting, can be used as animals feed supplements or in producing compost fertilizer.

There are basically three techniques for reusing organic wastes in fish culture: by fertilization of fish ponds with human or animal manure; by rearing fish in effluent-fertilized fish ponds; or by rearing fish directly in waste stabilization ponds. Fish farming is considered to have a great potential for developing countries because fish can be easily harvested and have a high market value. However, to safeguard public health in those countries where fish are raised on wastes, it is essential to have good hygiene in all stages of fish handling and processing, and to ensure that fish are consumed only after being well cooked.

Chitin and chitosan are non-toxic, biodegradable polymers of high molecular weight and of same chemical structure. They are a nitrogenous polysaccharide which can be isolated from shells of crustaceans, such as shrimps and crabs. Chitin is a linear chain of acetyl glucosamine groups which is insoluble in water. Chitosin is obtained by removing acetyl group (CH_3-CO) from chitin molecules (a process called deacetylation). Chitosan has cationic characteristics, is soluble in most diluted acids and is able to form gel, granule, fiber and surface coating.

Chitin and chitosan have many useful applications in the environmental, food, cosmetic and pharmaceutical fields. They have been used in wastewater treatment and as food additives, disinfectants and soil conditioners. Chitin and chitosan are being used as components in the manufacturing of several cosmetic and medicinal products.

Since crustacean shells, abundant in nature, are usually disposed of as waste materials from households and food industries, converting them into valuable products, such as chitin and chitosan, should help to protect the environment and bringing financial incentives to the people. More details of chitin and chitosan production and their application are given in Chapter 6.

1.2.4 Indirect reuse of wastewater

The discharge of wastewater into rivers or streams can result in the self-purification process in which the microbial activities (mainly those of bacteria) decompose and stabilize the organic compounds present in the wastewater. Therefore, at a station downstream and far enough from the point of wastewater discharge, the river water can be reused in irrigation or as a source of water supply for communities located downstream. Figure 1.3 depicts typical patterns of dissolved oxygen (DO) sag along distance of flow of a stream receiving organic waste discharge. Type 1 pollution occurs when the organic waste load is mild and little DO is utilized by the bacteria in waste decomposition. At higher organic waste load (type 2 pollution), more oxygen is utilized by the bacteria, causing a greater DO sag and consequently a longer recovery time or distance of flow before the DO could reach the normal level again. Type 3 pollution has an over-loading of organic waste into the stream, resulting in the occurrence of anaerobic condition (zero DO concentration). This is detrimental to the aquatic organisms; the recovery time for DO will be much longer than those of the types 1 & 2 pollution. Although DO is an indicator of stream recovery from pollution discharge, other parameters such as the concentrations of pathogens and toxic compounds should be taken into account in the reuse of the stream water.

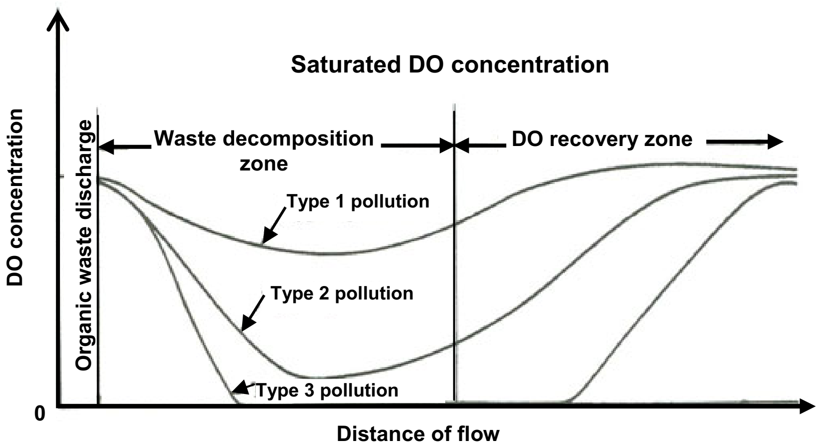

Figure 1.3 DO sag profile in polluted stream

Similarly, raw or partially treated wastewater can be injected into wells upstream and, through the processes of filtration, straining, and some microbial activities; good quality water can be deducted from wells downstream. The subject of groundwater recharge is presented in Chapter 8.

1.3 INTEGRATED AND ALTERNATIVE TECHNOLOGIES

Depending on local conditions, the above-mentioned technologies can be implemented individually or in combination with each other. For optimum use of resources, the integration of various waste recycling technologies in which the wastes of one process serve as raw material for another should be considered. In these integrated systems, animal, human and agricultural wastes are all used to produce food, fuel and fertilizers. The conversion processes are combined and balanced to minimize external energy inputs and maximize self-sufficiency. The advantages of the integrated system include (NAS 1981):

- Increased resource utilization,
- Maximized yields,
- Expanded harvest time based on diversified products,
- Marketable surplus, and
- Enhanced self-sufficiency.

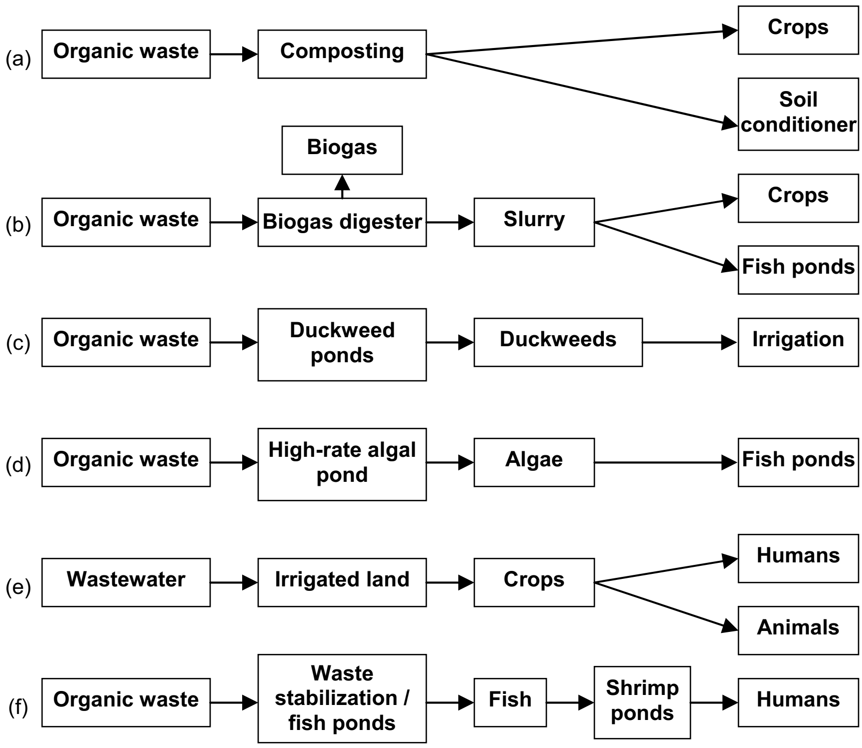

Figure 1.4 Some integrated systems of organic waste recycling program

Some of the possible integrated systems of organic waste recycling are shown in Figure 1.4. In scheme (a), organic waste such as excreta, animal manure or sewage sludge is the raw material for the composting process; the composted product then serves as fertilizers for crops or as soil conditioner for infertile soil. Instead of composting, scheme (b) has the organic waste converted into biogas, and the digested slurry serves as fertilizer or feed for crops or fish ponds, respectively. Schemes (c)-(f) generally utilize organic waste in liquid form and the biomass yields such as weeds, algae, crops and fish can be used as food or feed for other higher life forms, including human beings, while treated wastewater is discharged to irrigated land. The integrated systems that combine several aspects of waste recycling at small- and large-scale operations have been tested and/or commercially implemented in both developing and developed countries.

An alternative concept, that has high application potential for unsewered areas, is decentralised wastewater management. This concept implies the collection, treatment and disposal or reuse of wastewater from individual, or clusters of homes, at or near the point of waste generation (for example, a decentralized system may employ composting toilets to treat feces and other organic solid wastes, while the wastewater liquids (from bathroom and washing) can be treated by constructed wetlands). The composted products are used as organic fertilizers, which effluent of the constructed wetlands can be used for irrigation of crops and lawns. Some examples of the above systems that have been in successful operation on a commercial scale are described below.

1.3.1 Kamol Kij Co. Rice Mill Complex and Kirikan Farm, Thailand (Ullah 1979)

The Rice Mill Complex (area 18 ha) and Kirikan Farm (area 81 ha), owned by the same company, are located in Pathumthani Province, about 30 km north of Bangkok. Figure 1.5 shows the recycling of by-products or wastes generated from the rice milling units which produce about 500 tons per day of parboiled and polished rice from purchased paddy. Rice husks are burned to produce the energy needed for parboiling, paddy drying and oil extraction. The husk ash is mixed with clay to make bricks, and the white ash from the kiln, containing about 95 percent silica, is sold for use in making insulators and abrasives.

Fine bran from the rice mill is passed to the oil extraction plant to produce crude vegetable oil about 20 percent in concentration; this crude oil is sold to a vegetable oil refinery factory to produce edible vegetable oil. The defatted rice bran is used as animal feed at Kirikan Farm.

The Kirikan Farm, one of the biggest integrated farms in Thailand, maintains livestock, fish and crops, as shown in Figure 1.6. There are approximately 7,000 ducks, 6,500 chickens and 5,000 pigs being raised there, using feed from the rice mill defatted bran and other feed components. The farm could sell about 430,000 duck eggs and 1.2 million chicken eggs in a year.

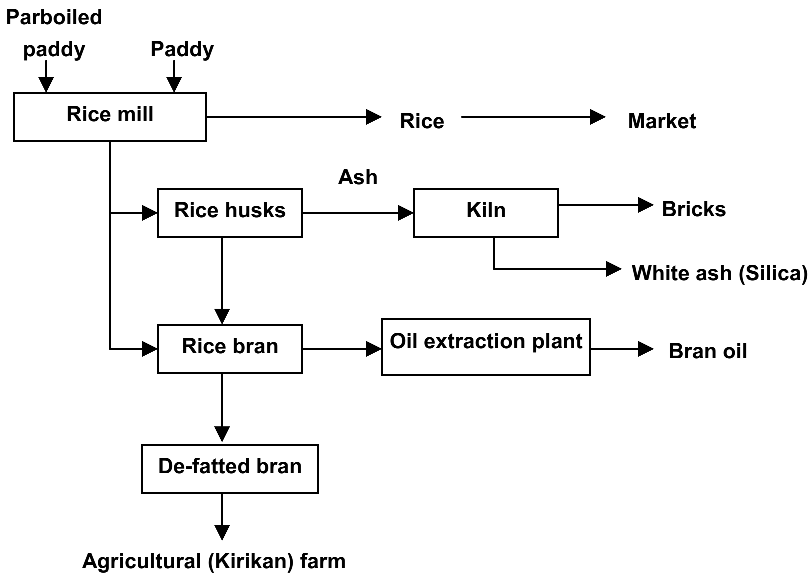

Figure 1.5 Kamol Kij Co. Rice Mill complex, Thailand

The chicken pens are located above the pigsties so that the waste food and chicken droppings are consumed by the pigs. The manure from pigs, chickens and ducks is fed to fish ponds. Part of the pig manure is used as influent to the biogas digester to produce biogas for use in the farm. The fish ponds are cultured with *Pangasius,* Tilapia and *Clarias* and good fish yields are reported. The crops cultivated on the farm are sugar cane, potatoes, beans, bananas, mangoes and some vegetables. These crops are fertilized with the fish pond water and the biogas digester slurry.

1.3.2 Maya Farms, the Philippines

The 24-ha Maya Farms complex maintains 15,000 pigs and markets nearly twice that number annually (NAS 1981). The biogas plants have been established primarily to control the pollution from its integrated piggery farms, meat processing and canning operations. There are various kinds of biogas digesters, but the large-scale, plug-flow digesters are part of the waste recycling system. About 7.5 tons of pig manure is fed daily into the three biogas digesters; the size of each digester is 500 m^3 and each produces approximately 400 m^3 of biogas per day. The biogas replaces liquefied petroleum gas (LPG) for cooking and other heating operations in the canning plant. It also replaces steam for heating the scalding tank in the slaughterhouse and the cooking tank in the meat processing plant; and replaces the electric heaters in the drying rooms. The farms use biogas to run the gas refrigerators and electric generators, and converted gas engines to replace the electric motors for deep-well pumping (Maramba 1978).

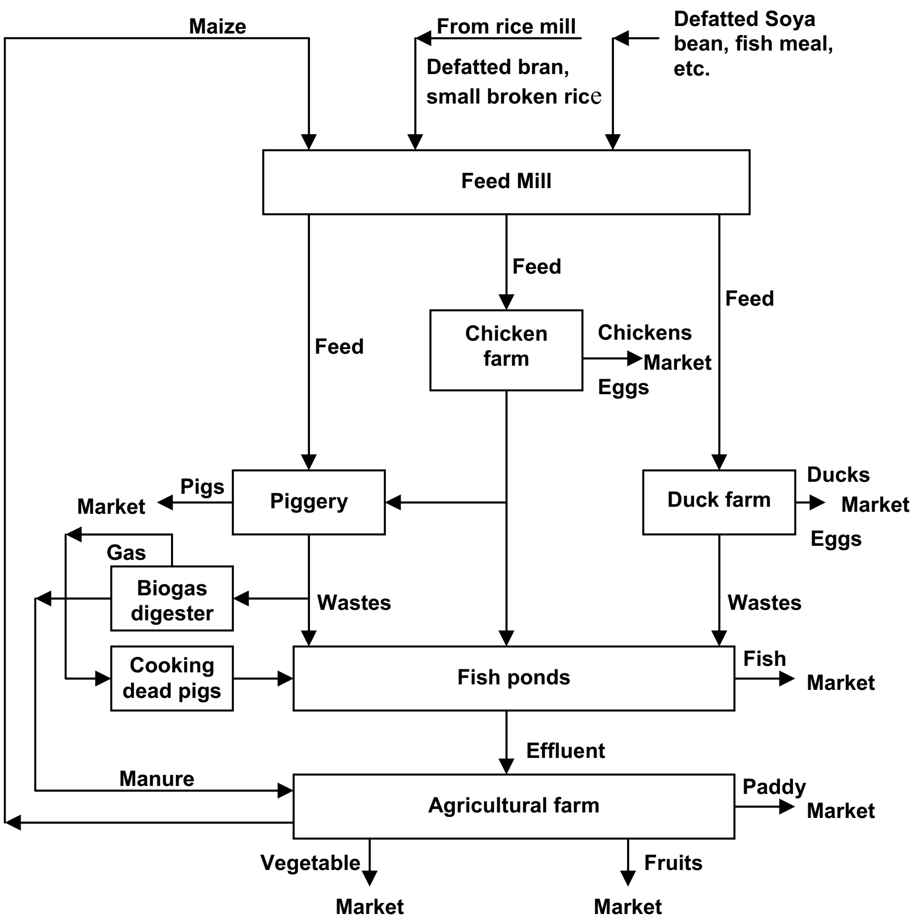

Figure 1.6 Flow diagram of Kirikan Farm, Thailand

Digested slurry from the above biogas digesters is conditioned in a series of waste stabilization ponds and used as a partial ration (10 percent) in the pig feed. Treatment of the sludge supernatant (liquid portion) is through a combination of planktonic algae (*Chlorella*) and fish (Tilapia) ponds (Diaz and Golueke 1979).

1.3.3 Werribee Farm, Australia

The Werribee Farm was established at the inception of the Melbourne Sewerage System and has been in operation since 1897. It is situated in an agricultural area 33 km from Melbourne and has a frontage of 21 km to Port Phillip Bay. Of the Melbourne sewage flow received at the Farm, 70 percent is municipal waste with the remainder coming from trade and industrial wastes. Table 1.3 shows the infrastructure and facilities for sewage treatment, and data of livestock being raised at the Farm.

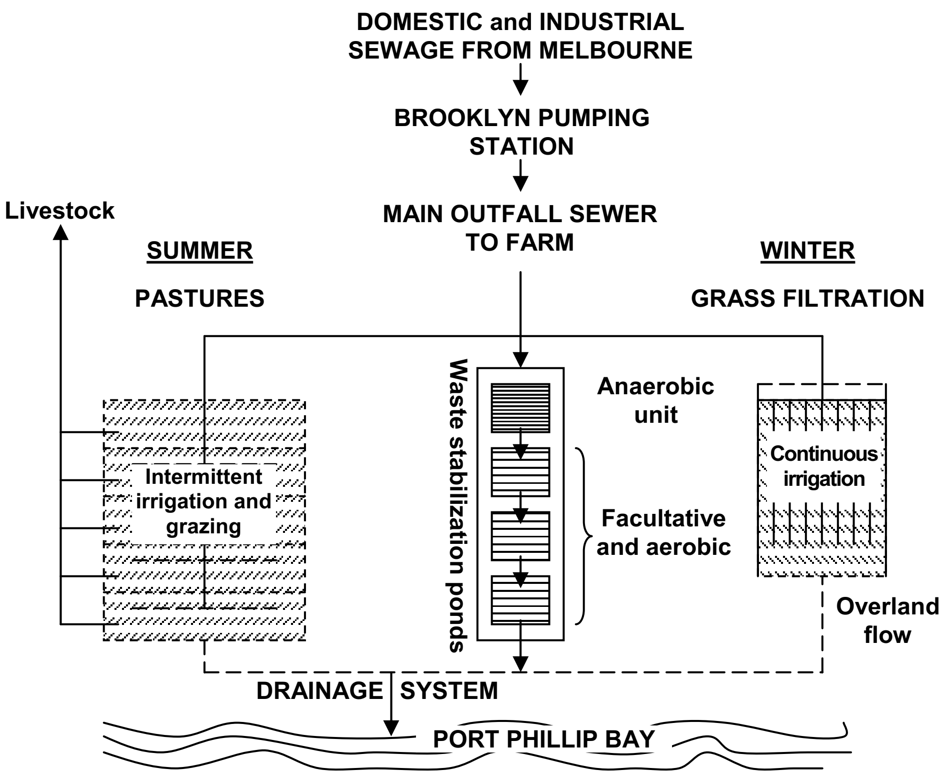

Figure 1.7 Sewage purification and waste recycling-Werribee Farm, Australia (Barnes 1978)

Figure 1.7 shows the sewage purification and waste recycling schemes in operation at Werribee Farm, consisting of three treatment processes, namely waste stabilization ponds (or lagooning), land filtration (or irrigation) and grass filtration (or overland flow). Sewage is primarily treated by a series of waste stabilization ponds. Sewage irrigation through land filtration and cattle grazing of grass are conducted in the summer period. The annual gross return from the sale of livestock is of the order of Australian $1 million. Grass filtration of sewage is employed during the winter season. A description of methods of land treatment of wastewater is given in Chapter 8. The final effluent from the Farm is discharged into the sea at Port Phillip Bay without causing any serious environmental impact to the marine ecosystem. The Werribee Farm treatment complex supports an abundance of wildlife, including over 250 species of birds and several species of fauna and flora (Bremner and Chiffings 1991).

Table 1.3 Facts about the Board of Works Farm - Werribee, Austrialia (Bremner & Chiffings 1991)

Area	10,850	ha
Road construction	231	km
Fencing erected	App. 2,024	km
Channels constructed	853	km
Drains constructed	666	km
Annual rainfall	530	mm
Annual evaporation	1350	mm
Average daily flow	470,000	m^3/day
Sewage BOD_5	510	mg/L
Sewage SS	450	mg/L
Area used for purification of sewage		
Land filtration	3,830	ha
Grass filtration	1,520	ha
Lagoon treatment	1,500	ha
Livestock		
Cattle on farm	12,000	
Cattle bred on farm during year	4500	
Sheep on farm	25,000-70,000	

BOD_5 = 5-day biochemical oxygen demand
SS = Suspended solids

The Werribee Farm occupies almost 11,000 ha of land and treats an average of 500 million litres of sewage and industrial waste daily. Under the upgrading plan, the land and grass filtration treatment processes were phased out in 2005 and all sewage is being treated in lagoons which cover about 1,820 ha of land. Biogas is being collected from the first 3 covered anaerobic lagoons to generate electricity for uses in the treatment operation. Treated effluent form the maturation ponds is used to irrigate padlocks, previously used for land and grass filtration. These padlocks are used for cattle and sheep grazing.

1.3.4 Decentralized sanitation in western Africa

A research project on the use of composted organic wastes from urban households for phytosanitary purposes in the peri-urban agriculture in Western Africa was reported by Streiffeler (2001). In Senegal, the organic materials, separated from household's solid wastes, were composted for 2-3 months before uses in agriculture. Temperature rises in the compost heap were up to 70°C, sufficient to kill any pathogenic organisms present in the waste materials. The compost extracts were applied to plants that were most susceptible to diseases, such as tomato and cassava, and the preliminary results obtained showed some reduced rates of plants succumbing to diseases. The project outcomes suggested the benefits of using organic compost as fertilizers and for controlling of plants diseases.

1.3.5 Cogeneration at Rayong Municipality, Thailand (http://www.cogen3.net)

The Rayong municipality has a population of about 60,000 in the year 2006 and is located 180 km east of Bangkok city. With financial support from the central government, it has built a solid waste treatment facility for waste stabilization, electricity generation and production of soil conditioner. As shown in Figure 1.8, the facility costing US$ 4.3 million includes an anaerobic digestion tank, a biogas storage dome and a biogas fired co-generator. It is designed to handle at full capacity 25,550 tons of municipal solid wastes annually (or 70 tons per day), with the projected biogas production of 2.2 million cubic meters per year, electricity generation of 5,100 MWh and production from the digested solids wastes of 5,600 tons per year of soil conditioners containing 35 % moisture content. Financial gains from the sales of mainly electricity and soil conditioners are expected to pay the invested cost in 10 years.

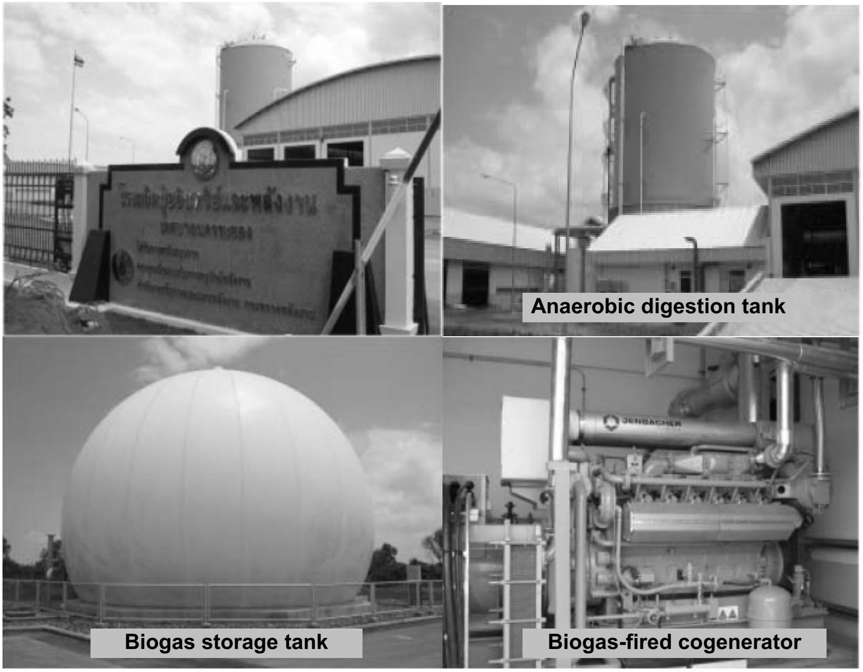

Figure 1.8 Solid waste treatment facility of Rayong municipality, Thailand. (http://www.cogen3.net)

1.4 FEASIBILITY AND SOCIAL ACCEPTANCE OF WASTE RECYCLING

The feasibility of a waste recycling scheme depends not only on technical and economic aspects, but also on social, cultural, public health and institutional considerations. Although waste recycling has been in practice successfully in many countries (both developed and developing), as cited in examples in section 1.3, a large number of people still lack understanding and neglect the benefits to be gained from these waste recycling schemes. Waste recycling should not aim at only producing food or energy. In considering the cost-effectiveness of a waste recycling scheme, unquantifiable benefits to be gained from pollution control and public health improvement should be taken into account. Because human excreta and animal manure can contain several pathogenic microorganisms, the recycling of these organic wastes has to be undertaken with great care; the public health aspects of each waste recycling technology are discussed in the following chapters.

Institutional support and cooperation from various governmental agencies in the promotion, training and maintenance/monitoring of waste recycling programs are also essential for success.

Since the success of any program depends greatly on public acceptance, the communities and people concerned should be made aware of the waste recycling programs to be implemented, their processes, and advantages and drawbacks. A public opinion survey was conducted in 10 communities in Southern California, USA, (Stone 1976) to assess the social acceptability of water reuse. For lower contact uses (such as in irrigating parks/golf courses, factory cooling, toilet flushing, and scenic lakes), public attitudes are largely accepting; besides, treatment costs are generally low due to the requirement for a lesser degree of treatment, and adverse impacts on public health are minimized. In contrast, the reuse of wastewater for body contact uses (such as in boating/fishing, beaches, bathing, and laundry) produced more neutral or negative attitudes, while those for human consumptive reuses (such as in food canning, cooking, and drinking) were not acceptable to the people surveyed.

A recent report by Metcalf *et al.* (2006) indicated that in Florida U.S.A., irrigation with reclaimed water has become common and demand for the reclaimed water is highest during the dry season. The advanced wastewater treatment plant of Tampa, Florida, currently produces 190,000 - 227,000 m^3/day of reclaimed water and the flow rate is expected to increase to 265,000 m^3/day within the next 20 years. The use of the reclaimed water for irrigation and stream augmentation is expected to offset about 98,400 m^3/day of potable water. Another 30,300 m^3/day of the reclaimed water will also be available for natural systems restoration and aquifer recharge.

The assessment of public acceptance for wastewater reuse has not been undertaken or is rarely, if at all, conducted in developing countries. Because several countries such as China, India, and Indonesia have been recycling either human or animal wastes for centuries, and due to their socio-economic constraints, the social acceptability for wastewater reuses should be more positive than those in developed countries. A recent study in southern Thailand by Schouw (2003) found the recycling of human waste nutrients through composting toilets and irrigation of septic effluents to be socially acceptable. The uses of composting toilet for excreta treatment and waste stabilization ponds for the treatment of sullage (wastewater from kitchens, bathrooms and washing) were considered to be the most environmentally feasible.

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1.6 EXERCISES

1.1 List the major types of organic wastes available in your own country and give examples of organic waste recycling practices being undertaken there.

1.2 Based on the data given in Table 1.1, give reasons why the percent coverage of urban and rural sanitation in the year 2000 is not much higher than in the year 1990. Suggest measures to increase these coverage percentages.

1.3 Find out the current practices of agricultural fertilization in your country with respect to the use of chemical fertilizer. How can you convince the farmers to use more organic waste fertilizer?

1.4 Conduct a survey, through interviews or questionnaire, about the public acceptance of the following methods of organic waste recycling: composting, biogas, production, algal production, fish production and crop irrigation. Based on the survey results, rank the public preference of these waste recycling methods and discuss the results.

1.5 You are to visit an agro-based industry or farm and investigate the present methods of waste treatment/recycling being undertaken there. Determine the potential or improvements that can be made at the industry or farm on the waste management aspects.

1.6 From the website of the Millenium Development Goals (www.un.org/millenium goals), find out: (a) which Goals and Actions are most relevant to the situations of your country and (b) measures being implemented in your country to achieve these goals.

2

Characteristics of organic wastes

Almost all kinds of organic wastes can be recycled into valuable products according to the technologies outlined in Chapter 1. In designing facilities for the handling, treatment, and disposal/reuse of these wastes, knowledge of their nature and characteristics is essential for proper sizing and selecting of a suitable technology. This chapter will describe characteristics of organic wastes generated from human, animal and some agro-industrial activities. Pollution caused by these organic wastes, and possible diseases associated with the handling and recycling of both human and animal wastes are described. A section on cleaner production is presented to emphasize the current trend of waste management. The analysis of physical, chemical and biological characteristics of the organic wastes can be done following the procedures outlined in "Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF 2005) and Official Methods of Analysis of the Association of Official Analytical Chemists (AOAC 2000); while the significance of these characteristics for waste treatment and recycling can be found in Chemistry for Environmental Engineering and Science (Sawyer *et al.*

2003) and Wastewater Engineering: Treatment, Disposal and Reuse (Metcalf and Eddy Inc. 2003).

2.1 HUMAN WASTES

Excreta is a combination of feces and urine, normally of human origin. When diluted with flushing water or other grey water (such as from washing, bathing and cleansing activities), it becomes domestic sewage or wastewater. Another type of human wastes, called solid wastes, refers to the solid or semi-solid forms of wastes that are discarded as useless or unwanted. It includes food wastes, rubbish, ashes and residues, etc.; in this case, the food wastes which are mostly organic are suitable to be recycled.

The quantity and composition of human excreta, wastewater and solid wastes vary widely from location to location depending upon, for example, food diet, socio-economic factors, weather and water availability. Therefore, generalized data from the literature may not be readily applicable to a specific case and, wherever possible, field investigation at the actual site is recommended prior to the start of facility design.

2.1.1 Human excreta

Literature surveys by Feachem *et al.* (1983) found the quantity of feces production in some European and North American cities to be between 100 to 200 g (wet weight) per capita daily, while those in developing countries are between 130-520 g (wet weight) per capita daily. Most adults produce between 1 to 1.3 kg urine depending on how much they drink and the local climate. The water content of feces varies with the fecal quantity generated, being between 70-85%. The composition of human feces and urine is shown in Table 2.1. The solid matter of feces is mostly organic, but its carbon/nitrogen (C/N) ratio is only 6-10 which is lower than the optimum C/N ratio of 20-30 required for effective biological treatment. If such processes as composting and/or anaerobic digestion are to be employed for excreta treatment, other organic matters high in C content are needed to be added to raise the C/N ratio. Garbage (food wastes), rice straw, water hyacinth, and leaves are some easily available C compounds used to mix with excreta. A person normally produces from 25 to 30 g of BOD_5 daily through excreta excretion.

In areas where sewerage systems are not available, excreta is commonly treated by on-site methods such as septic tanks, cesspools, or pit latrines. Periodically (about once in every 1-5 years), septage or the sludge produced in septic tanks and cesspools needs to be removed so that it does not overflow from the tanks to clog the soakage pits (Figure 2.1) or the drainage trenches (soakage pit and/or drainage trench is a unit where septic tank/cesspool overflow flows into and from where it seeps into the surrounding soil where the soil microorganisms will biodegrade its organic content). The most satisfactory method of septage removal is to use a vacuum tanker (size about 3-10 m^3) equipped with a pump and a flexible suction hose (Figure 2.1). If vacuum tankers are not available, the septage has to be manually collected by shovel and buckets; in this case the laborer who does the septage emptying can be subjected to disease contamination from the septage, and the practice is considered to be unaesthetic and unhygienic.

Table 2.1 Composition of human feces and urine[a]

	Feces	**Urine**
Quanity (wet) per person per day	100-400 g	1 - 1.31 kg
Quanity (dry solids) per person per day	30 - 60 g	50 -70 g
Moisture content	70 -85 %	93 - 96 %
Approximate composition (percent dry weight)		
Organic matter	88 - 97	65 - 85
Nitrogen (N)	5.0- 7.0	15 – 19
Phosphorus (as P_2O_5)	3.0 - 5.4	2.5 - 5.0
Potassium (as K_2O)	1.0 - 2.5	3.0 - 4.5
Carbon (C)	44 - 55	11.0 - 17.0
Calcium (as CaO)	4.5	4.5 -6.0
C/N ratio	~ 6 -10	1
BOD_5 content per person per day	15 - 20 g	10 g

[a] Adapted from Gotaas (1996) and Feachem *et al.* (1983)

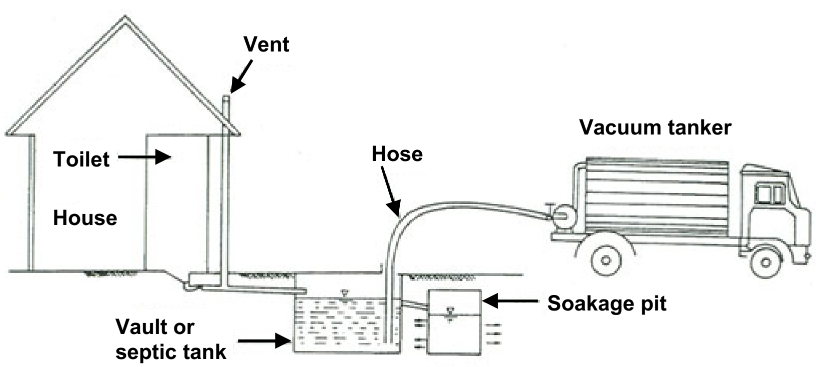

Figure 2.1 Vacuum tanker removing septage

Septage is characterized by high solid and organic contents, large quantity of grit and grease, great capacity to foam upon agitation, and poor settling and dewatering characteristics. A highly offensive odor is often associated with brown to black septage. The composition of septage is highly variable from one location to another. This variation is due to several factors including: the number of people utilizing the septic tank and their cooking and water use habits, tank size and design, climatic conditions, septage pumping frequency, and the use of tributary appliances such as kitchen waste grinders and washing machines.

Table 2.2 summarizes the septage characteristics in the U.S.A. and Europe/Canada as reported in the literature. The last column of this table shows the suggested design values of the septage characteristics for use as guidelines in the design and operation of septage handling and treatment facilities. Characteristics of some septage in Asia are shown in Table 2.3.

Brandes (1978) reported that longer detention time of septage in the tanks contributed to better decomposition of organic materials and, consequently, to lower amounts of septage pumped out per year. He found the septage accumulation rate for the residents of Ontario, Canada, which is applicable for septage disposal and treatment planning, to be approximately 200 L per capita yearly. Septage accumulation rates under Japanese conditions were estimated to be 1-1.1 L per capita daily (or 365-400 L per capita yearly) (Pradt 1971). However, field investigations at the actual site are strongly recommended prior to the inception of detailed planning and design of septage treatment facilities. Because of its concentrated characteristics, septage needs to be properly collected and treated prior to disposal. On the other hand, its concentrated form would be advantageous for reclaiming the valuable nutrients contained in it.

Human excreta that is deposited in pit latrines normally stay there under anaerobic conditions for 1-3 years prior to being dug out for possible reuse as a soil conditioner or fertilizer. The rather long period of anaerobic decomposition in pit latrines will cause the excreta to be well stabilized and most pathogens inactivated.

2.1.2 Wastewater

Urban cities in developed countries and many cities in developing countries have sewerage systems to carry wastewater from households and buildings to central treatment plants. This wastewater is a combination of excreta, flushing water and other grey water or sullage, and is much diluted depending on the per capita water uses. According to White (1977), the volume of water used ranges from a daily mean consumption per person of a few L to about 25 L for rural consumers without tap connections or standpipes. The consumption is 15-90 L for those with a single tap in the household, and 30-300 L for those with multiple taps in the house.

Table 2.2 Physical and chemical characteristics of septage, as found in the literature, with suggested design values[a,b] (adapted from U.S. EPA 1994)

Parameters	United States				Europe/Canada				EPA mean	Suggested design value
	Average	Minimum	Maximum	Variance	Average	Minimum	Maximum	Variance		
TS	34,100	1,130	130,475	115	33,800	200	123,860	619	38800	40,000
VSS	9030	95	51500	542	29900	4000	52,370	13	8,720	10,000
BOD_5	6480	440	78600	179	8340	700	25000	36	5,000	7,000
COD	31900	1500	703000	469	28975	1300	114870	88	42,850	15,000
TKN	550	66	1060	16	1070	150	2570	17	680	700
Total P	210	20	760	38	155	20	640	32	250	250
Grease	5600	210	23370	112	-	-	-	-	9,090	8,000
pH	-	1.5	12.6	8	-	5.3	9	-	6.9	6.0
LAS[c]	-	110	200	2	-	-	-	-	157	150
Total coliforms	-	10^7	10^9	-	-	-	-	-	-	-
Fecal coliforms	-	10^6	10^8	-	-	-	-	-	-	-

[a] Values expressed as mg/L, except for pH, which is unitless and total and fecal coliforms which are no./100 mL
[b] The data presented in this table were complied from many sources. The inconsistency of individual date sets results in some skewing of the data and discrepancies when individual parameters are compared. This is taken into account in offering suggested design value
[c]LAS = linear alkylbenzene sulfonate, used in making detergents

Table 2.3 Characteristics of septage in Asia[a]

	Japan[b]	**Bangkok, Thailand**[c]
pH	7-9	7-8
TS	25,000-32,000	5,000-25,400
TVS		3,300-19,300
TSS	18,000-24,000	3,700-24,100
VSS	3,500-7,500	-
BOD_5	4,000-12,000	800-4,000
COD	8,000-15,000	5,000-32,000
NH_3-N	-	250-340
Total P	800-1,200	-
Total coliforms, no/100mL	10^6-10^7	10^6-10^8
Fecal coliforms, no/100mL	-	10^5-10^7
Bacteriophages, no/100 mL	-	10^3-10^4
Grit (%)	0.2-0.5	-

[a] Values expressed as mg/L, except for pH and those specified
[b] Date from Magara *et al.* (1980)
[c] Data from Arifin (1982) and Liu (1986)

It should be noted that households with per capita water consumption less than 100 L per day may produce wastewater containing very high solids content which could possibly cause sewer blockage. The strength of a wastewater depends mainly on the degree of water dilution which can be categorized as strong, medium, or weak as shown in Table 2.4. These wastewater characteristics can vary widely with local conditions, hour of the day, day of the week, seasons, and types of sewers (either separate or combined sewers where storm water is included). It is seen from Table 2.4 that domestic wastewaters generally contain sufficient amounts of nutrients (based on BOD_5: N: P ratio) suitable for biological waste treatment and recycling, where microbial activities are employed.

In sewerless areas where septic tanks or cesspools are employed for wastewater treatment, the hydraulic retention time (HRT) designed for these units are only about 1-3 days to remove the settleable solids and retain the scum. Because of short HRT, the effluent from a septic tank or septic tank overflow is still obnoxious liquor, containing high concentrations of organic matter, nutrients, and enteric microorganisms. The septic tank effluent is normally treated through a subsurface soil absorption system or soakage pits (as shown in Figure 2.1) (Polprasert and Rajput 1982). Where land is not available for the treatment of septic tank effluent, the effluent can be transported, via small-bore sewers, to a central wastewater treatment/recycling plant (small-bore sewers have diameters smaller than conventional sewers and carrying only liquid effluents from septic tanks or aqua privies). The characteristics of septic tank effluent are more or less similar to those of the wastewater (Table 2.4), but contain less solid content.

Table 2.4 Typical characteristics of domestic wastewater (all values are expressed in mg/L)

	Concentration		
Parameters	**Strong**	**Medium**	**Weak**
BOD_5	400	200	100
COD	800	400	250
Org.-N	25	15	8
NH_3	50	25	12
Total-N	70	40	20
Total-P	15	8	4
Total solids	1200	720	350
Suspended solids	400	200	100

Data adapted from Metcalf and Eddy Inc.(2003)

2.1.3 Solid wastes

Solid wastes generated from human activities include those from residential, commercial, street sweepings, institutional and industrial categories. Table 2.5 is a comparative analysis of solid waste characteristics of some developing and developed countries. The percentages of food wastes (organic matter) were 60 -70 for the developing countries (Thailand and Egypt) which were a few folds higher than those of the developed countries (U.K. and U.S.A.). On the other hand, paper and cardboard were found to be higher in the solid wastes of the developed countries. The quantity of solid waste generation is generally correlated with the per capita income and affluence, i.e. the higher the income the greater the amount of solid wastes generated. The global range of solid waste generation is 0.2-3 kg per capita daily (Pickford 1977). Solid waste generation rates of less than 0.4 kg per capita daily can be applied to some cities of developing countries and a range of 1.0 – 1.5 kg per capita daily for major cities and tourism areas. Generation rates greater than 2 kg per capita daily are applicable to several cities in the U.S.A. (Cook and Kalbermatten 1982; and Pickford 1977).

Since the food waste portion of the solid wastes is suitable for recycling (e.g. through composting and anaerobic digestion), it should be ideally stored and collected separately for this purpose. However, for convenient and practical reasons, food waste is normally collected together with other kinds of wastes to be processed and treated at a solid waste treatment plant. If composting is to be employed as a means to stabilize and produce fertilizer from the solid wastes, several methods of solid waste processing have to be utilized to separate out the food waste. These processing methods include mechanical size reduction and component separation, the details of which can be found in the book Integrated Solid Wastes Management (Tchobanoglous *et al.* 1993) and Handbook of Solid Waste Management (Wilson 1977). The subject of composting is described in Chapter 3 of this book.

Table 2.5 Comparative solid wastes analysis[a]

	Thailand [b]	**Egypt** [c]	**U.K** [d]	**U.S.A** [e]
Food wastes (organic)	63.6	70	17.6	9
Paper and card board	8.2	10	36.9	40
Metals	2.1	4	8.9	9.5
Glass	3.5	2	9.1	8
Textiles	1.4	2	2.4	2
Plastics and rubber	17.3	1	1.1	7.5
Miscellaneous, incombustible	3.2	10	21.9	4
Miscellaneous, combustible	0.7	1	3.1	20
Bulk density, kg/L	0.28	-	0.16	0.18

[a] unit in % wet weight
[b] http://www.mnre.go.th
[c] Cook and Kalbermatten (1982)
[d] Department of Environment (1971)
[e] Tchobanoglous *et al.* (1993)

2.2 ANIMAL WASTES

The amount and composition of animal wastes (feces and urine) excreted per unit of time also vary widely. They depend on various factors such as the total live weight of the animal (TLW), animal species, animal size and age, feed and water intake, climate, and management practices, etc. For design of facilities for animal waste collection and treatment, measurements and samples should be taken at the farm site or (if the farm is not built) at similar sites. For planning purpose, Taiganides (1978) suggests that the general guideline values given in Table 2.6 may be used. Young animals excrete more waste per unit of TLW than mature animals. The quantities of wastewater or wastes to be handled would, in general, be larger than those given in Table 2.6, due to the addition of dilution water, washwater, moisture absorbing materials and litter, etc.

Table 2.7 shows the approximate weights of animals, the quantity of waste produced and their BOD_5 values. The annual production of nutrients from animal wastes is given in Table 2.8. During storage of animal wastes, a considerable portion of N which exists in the form of ammonia (NH_3) is lost through NH_3 volatilization.

Table 2.6 Bioengineering parameters of animal wastes (Taiganides 1978)

Parameters	Symbol	Units	Pork pigs	Laying hens	Feedlot beef	Feedlot sheep	Dairy cattle
Wet waste	TWW	%TLW/day	5.1	6.6	4.6	3.6	9.4
Total solids	TS	%TWW	13.5	25.3	17.2	29.7	9.3
		%TLW/day	0.69	1.68	0.7	1.07	0.89
Volatile solids	TVS	%TS	82.4	72.8	82.8	84.7	80.3
		%TLW/day	0.57	1.22	0.65	0.91	0.72
Biochemical oxygen demand	BOD_5	%TS	31.8	21.4	16.2	8.8	20.4
		%TVS	38.6	29.4	19.6	10.4	25.4
		%TLW/day	0.22	0.36	0.13	0.09	0.18
COD/BOD_5 ratio	COD/BOD_5	ratio	3.3	4.3	5.7	12.8	7.2
Total nitrogen	N	%TS	5.6	5.9	7.8	4.0	4.0
		%TLW/day	0.039	0.099	0.055	0.043	0.043
Phosphate	P_2O_5	%TS	2.5	4.6	1.2	1.4	1.1
		%TLW/day	0.017	0.077	0.008	0.015	0.010
Potash	K_2O	%TS	1.4	2.1	1.8	2.9	1.7
		%TLW/day	0.01	0.035	0.013	0.031	0.015

TLW = Total live weight of animal

For systems handling animal wastes as solids (>30%TS), N losses will range from 20% in deep lagoons to 55% for open feedlots. For animal waste liquid handling systems (<12%TS), N loses can range from about 25 % in anaerobic lagoons to 80 % for aerated systems (Taiganides 1978). P and K are physically and chemically less mobile than N. However, when applied to land the actual amounts of nutrients available to crops can be much less than those shown in Table 2.8 because of nutrient loss through soil leaching and the inability of crops to utilize the nutrients effectively, etc.

2.3 AGRO-INDUSTRIAL WASTEWATERS

This section will describe six types of agro-industries namely tapioca, palm oil, sugar cane, brewery, slaughter house, and fruit and vegetables. The general processes of the above industries and the quantity and characteristics of waste generation are presented. The processing diagrams of each agro-industry will include the sources of waste generation which should be useful for the environmental engineers and scientists to understand the waste characteristics and to investigate means to reduce waste generation at the industries.

Table 2.7 Waste production by various animals (Adapted from Lohani and Rajagopal 1981)

Animal	Average weight of animal (kg)	Total waste[a] (kg/head per day)	BOD_5 (kg/head per day [b])
Beef cattle	360	18-27	0.45-0.68
Dairy cattle (milk cows, replacement heifers, breeding stock)	590	44	0.9
Swine	45	-	-
Chickens:			
Broilers	-	0.05	0.0044
Laying hens	-	0.06	0.0044
Sheep and lambs	-	7.0	0.16
Turkeys	7	0.41	0.023
Ducks	1.6	-	0.017
Horses [c] (pleasure, farm racing)	-	37	0.36

[a] Total excreta including feces and urine.

[b] All units for waste and BOD_5 production are in kg/head/day except for those for chickens (broilers and laying hens) in kg/kg of bird/day as indicated.

[c] Manure for broilers and horses is mixed with bedding material or litter.

2.3.1 Tapioca industry

Tapioca, also known as cassava or manioc, is grown in most tropical areas of the world. The root of the plant contains approximately 20 percent starch in a cellulose matrix. Tapioca starch is in particular demand for sizing paper or fibres and is also used in food industry.

Tapioca products include pellets, chips and flour. The production of pellets has been increasing steadily, due to increase in demands of pellets as animal feeds from European countries (Unkulvasapaul 1975).

Production of pellets and chips are not water-using processes and hence are not causes of pollution. On the other hand, the production of tapioca flour requires large quantities of water and the resulting wastewaters are highly polluting. About 5 to 10 m^3 of water is used to process one ton of input root, or about 30 to 50 m^3 of water is used per ton of starch produced. The wastewaters produced are organic in nature and highly variable in quantity and quality. They are characterized by high BOD_5 and SS values, with low pH and few nutrients (Jesuitas 1966).

Tapioca processing

The main products of tapioca roots are pellets, chips and flour. Most of these (about 90% by weight) are marketed / exported in the form of pellets.

The manufacture of tapioca products is seasonal: plants begin processing in June and thereon production increases steadily to a peak production period between September and January, then production falls off gradually and comes to a halt in April. A few larger plants operate throughout the year.

Chip and pellet production

Chips are manufactured by chopping the tapioca roots and then spreading them out on large concrete pads for drying. They are either transported directly to market or are pelletized before shipping overseas.

Table 2.8 Nutrient content of raw livestock wastes in kg per 500 kg live animal weight per day, and as influent wastewater to a treatment system (mg/L)[a]

	Raw waste characteristics							
	BOD_5		**TN**		**TP**		**TK**	
	(kg)	(mg/L)	(kg)	(mg/L)	(kg)	(mg/L)	(kg)	(mg/L)
Cattle	0.9	18,800	0.24	4,800	0.03	500	0.16	3,200
Beef	0.8	25,400	0.17	5,400	0.05	1,450	0.11	3,300
Pig	1.6	27,300	0.26	4,600	0.09	1,600	0.15	2,550
Poultry	1.7	43,600	0.42	11,100	0.15	4,000	0.15	4,000

[a]Adapted from Sukias and Tanner (2005)

Pellets are produced by pressing chips into a cylindrical shape under high pressure and raised temperature; a small quantity of waste pulp from the starch plant is also added for adhesive purposes. Sometimes, an even smaller quantity of rice bran is added to improve the nutritional value of the pellets.

Flour production

Tapioca starch is produced in two grades by two types of processes. The final quality of starch is, however, similar.

First grade tapioca processes

A typical flow diagram of the first-grade starch plant is illustrated in Figure 2.2. Roots, transported to the plant, should be processed within 24 hours to avoid degradation of the starch. The sand on the roots is first removed by dry rasping in a revolving drum and the peel is then removed by mechanical tumbling in a wash basin, from which the root washwater is derived. The roots are then mechanically crushed, releasing the starch granules from their surrounding cellulose matrix. Most of the cellulose material is removed by centrifugal means in a jet extractor and then by continuous centrifugation. The cellulose material or pulp is sold as poultry feed, provided it is fresh; or dewatered, dried and sold as animal feed. After primary centrifugation, the starch milk is sieved through a series of three sieves decreasing in pore size to assist in separating the starch from the small amount of pulp remaining. The recovered pulp is recycled to the jet extractor and the processed starch milk is led to a second centrifuge, from which wastewater is derived and by which a more concentrated starch is produced. After dewatering to a paste-like substance in a basket centrifuge, the product is spray dried and packed.

As shown in Figure 2.2, there are three main sources of wastewaters, namely that from the root washer, centrifuge 1 and centrifuge 2. These wastewaters are normally combined and treated prior for discharge or reuse. The wastewaters from centrifuge 1 and centrifuge 2 are sometimes called separator wastewater.

Second grade tapioca process

Second-grade tapioca plants are labour intensive, employing simple processes with little mechanization, and are mostly small private-enterprise operations. A typical process flow diagram is shown in Figure 2.3. The roots are washed in a wooden tank with revolving paddles; sand and clay particles as well as some peel are removed at this step. The washed roots are conveyed to the rasper, followed by filtration through nylon mesh supported by a large cylindrical drum. The starch is sprayed through and the pulp is slowly drawn off and collected for dewatering. The starch milk is then released into large concrete settling basins. After 24 hours settlement, the supernatant is removed by decantation. The surface of the starch cake on the bottom is washed; the starch is then resuspended and pumped to a second sedimentation basin. After 24 hours the supernatant is decanted and the surface is then washed again. The starch is then removed in large cakey chunks and spread on a heated concrete pad to dry.

After drying, the starch is packed. The supernatant and surface washwaters from the first and second settling basins are discharged or directed to a third settling basin. In the case where a third settling basin is available, the supernatant and the surface washwaters are allowed to settle for 24 hours before the supernatant is decanted and discharged. The bottom sediment is dredged about once every two months; the sediment is resuspended two times again as mentioned above, and the starch thus recovered is sold as a lower-grade starch.

Tapioca starch wastewater characteristics

The combined wastewater from tapioca starch production is composed mainly of root washwater and either the starch supernatant decanted from sedimentation basins or the separator wastewater, depending upon whether a second-grade or first-grade starch factory is being considered. First-grade and second-grade factories in Thailand commonly process in the order of 200 and 30 tons of tapioca root per day, respectively, and release wastewaters with unit mass emission rates (UMER values) as shown in Table 2.9. Designations A, B, C and D refer to wastewater sources shown in Figures 2.2 and 2.3.

The characteristics of tapioca starch wastewaters are summarized in Table 2.10. Root washwater contains high settleable solids, mainly sand and clay particles from the raw roots. The combined waste is acidic in nature, its pH ranging from 3.8 to 5.2, resulting from the addition of sulphuric acid in the extraction process and also from the release of some prussic acid by the tapioca root.

Tapioca starch wastewaters are highly organic but have relatively low nitrogen and phosphorus concentrations. The ratio of soluble BOD_5 to soluble COD in the settled separator waste is 0.6 - 0.8, indicating that the waste is biologically degradable. It is likely that biological treatment methods will be most economical for this organic waste.

The high BOD_5 and COD concentrations suggest that anaerobic biological processes, as the first-stage treatment, will be effective for organic reduction, and the biofuel by-products, such as CH_4 gas are useful for energy generation. The treated effluent, still high in organic and nutrient contents, can be further stabilized through agricultural or aquaculture reuse, as stated in section 1.2.

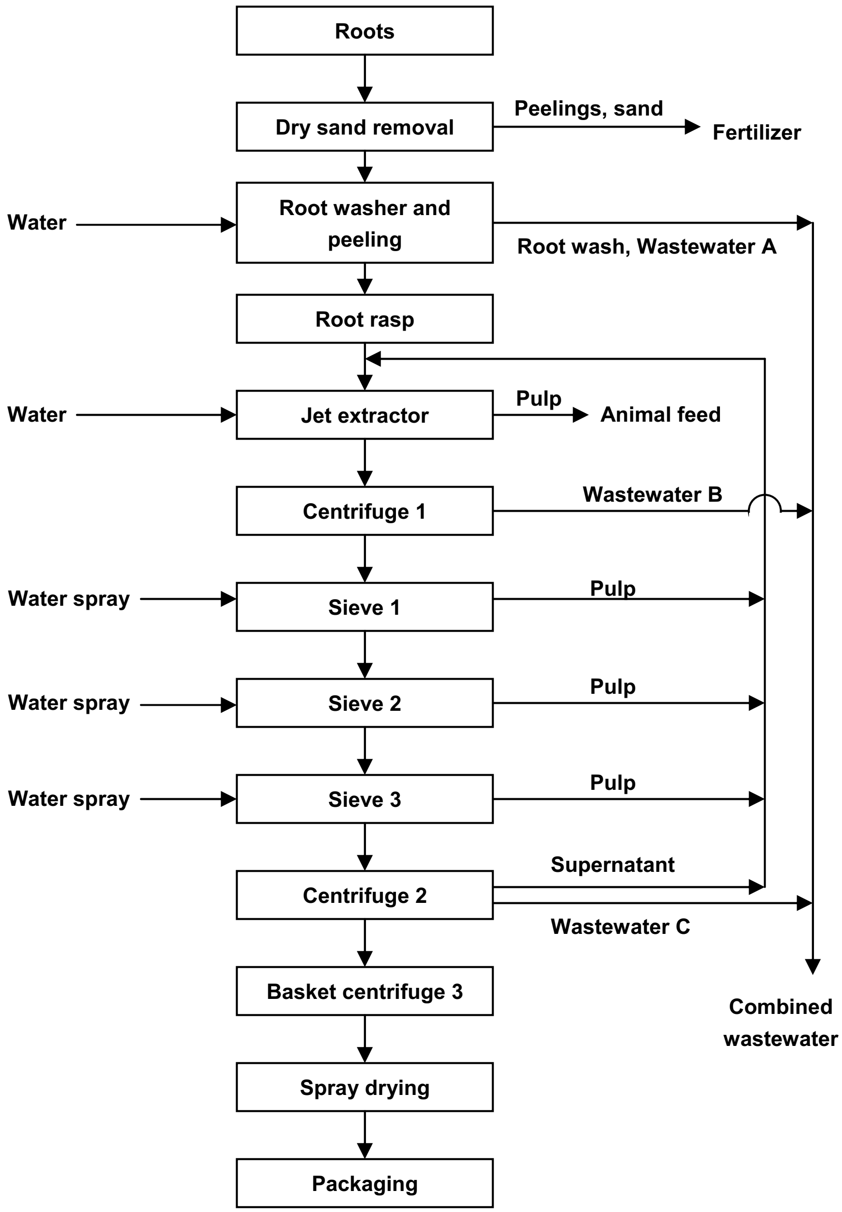

Figure 2.2 First-grade tapioca processing (Thanh 1984)

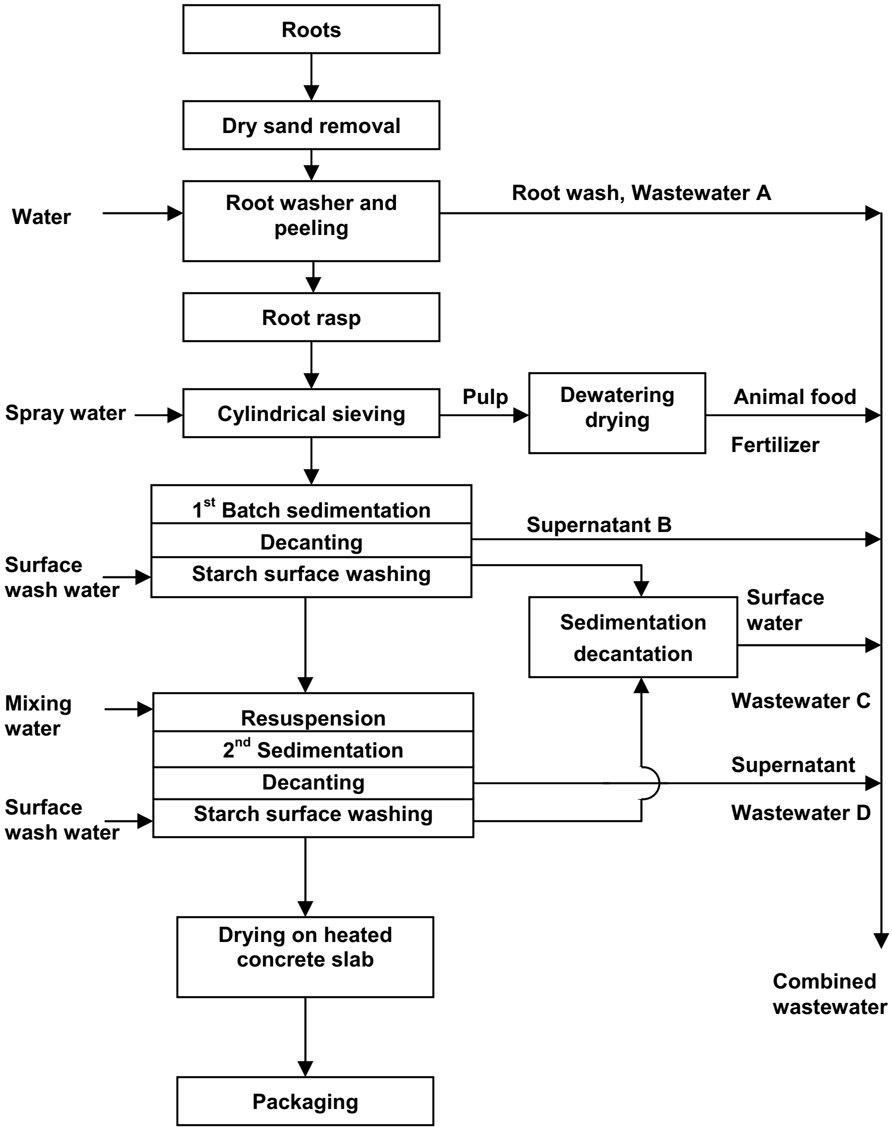

Figure 2.3 Second-grade tapioca processing (Thanh 1984)

Table 2.9 UMER[a] values of tapioca starch wastewater in g/kg root (Thanh 1984)

	Wastewater				
Characteristics	**A**	**B**	**C**	**D**	**Combined**
First-grade factory(Figure 2.2)					
COD	0.69	55.2	6	-	61.9
BOD_5	0.33	26.5	2.9	-	29.8
Suspended solids	0.54	10.5	3.7	-	15.7
Dissolved solids	4.91	46.3	9.6	-	60.8
Second-grade factory(Figure 2.3)					
BOD_5	1.8	44.8	2.1	2.1	48.8
Total solids	3.1	102.8	2.2	2.2	109.2
Suspended solids	3.1	83.5	0.6	0.6	87.2

[a] UMER = unit mass emission rate

2.3.2 Palm oil industry

Palm oil is basically a vegetable oil used mainly for human consumption. It is semi-solid, edible oil, extracted from the pulpy portion of the fruit wall of the palm fruit. The palm plants seem to have originated in the Guinea coast of West Africa and are now Malaysia's second most important crop. Almost all the palm oil produced in Malaysia and Thailand is used for margarine and other edible purposes. Due to the high oil prices, there has been increased use of palm oil to produce bio diesel in those countries that have oil palm plantation.

Extraction process

A general process flow diagram of a palm oil mill is shown in Figure 2.4. The freshly cut fruit bunches, delivered to the mill, are first loaded in cages mounted on rails and run directly into a horizontal sterilizer where steam is used to heat the fruits to about 140 °C at a pressure of 2.5 - 3.5 kg/cm^2 (35-45 psi) for 50 to 75 min.

The purpose of this sterilization is to de-activate the enzymes responsible for the break-down of oil into free fatty acids and to loosen the fruits from the stalks. Thereafter, the sterilized bunches are fed into a rotary-drum threshing or stripping machine, which separates the fruit from the bunches. The empty bunches drop into a conveyor belt that carries them into an incinerator and are burnt into ash, whereas the loose fruits are converted into a homogenous oily mash by a series of rotating arms (digester). The digested mash is then fed into a press for the extraction of crude oil (nuts must not be broken at this stage of the process).

Table 2.10 Characteristics of tapioca starch wastewater (After Thongkasame 1968 and Unkulvasapaul 1975)

Characteristics, mg/L (except as indicated)	Second-grade starch wastewater				First-grade starch wastewater		
	Washwater		Supernatant		Plant A		Plant B
	Range	Mean	Range	Mean	Separator wastewater	Wash water	Combined
BOD_5	300-2490	1190	1720-6820	4,150	3000-4000	200-1700	5550-7400
COD	610-6110	2700	4700-10000	7580	3100-13900	2000-4850	13300-19500
Suspended solids	290-4240	1880	470-1710	850	1480-8400	400-6100	1970-3850
NH_3-N	0-7.8	1.9	1.2-35.0	16	0-4.7	0-1.1	0
Org-N	0-67	32	4-109	70	19-39	14-18	86-115
Phosphorus	0-6.0	3.6	0-10.5	6.6	5.6-8.5	1.2-1.3	0
pH	3-4.6	4.2	2.6-4.0	3.4	3.4-4.2	4.2-7.1	3.8-5.2
DO	0-4.9	2.7	0-2.7	1	0	0.6-5.3	0
Acidity	-	-	-	-	670-860	20-220	135-1010

Nuts and fresh fiber are then separated to recover the nuts which are subsequently cracked to produce kernels for sale. The pressed fiber and some of the shells are usually burnt as fuel in the steam-raising boiler.

The extracted crude oil, consisting of a mixture of oil, water and some fine solid materials, is passed through a vibrating screen to remove the solid matters. Hot water is often added in this operation. A clarification tank is used to separate the oil by gravity and the oily sludge settles at the bottom. The clarified oil is further purified in a vacuum dryer prior to being pumped to a storage tank. The oil sludge, after straining and desanding, is centrifuged to recover the oil which is returned to the clarifier. The sludge is discharged into an oil trap, where further oil is recovered by heating the sludge with steam prior to discharge of the sludge to a waste treatment facility.

With respect to Figure 2.4, the sources of wastewater and sludge generated during palm oil milling are given below.

1. Sterilizer's condensates, cleansing of the sterilizers and floor washing at the sterilizer station.
2. Floor washing and desanding of the press station.
3. Steam condensates
4. Steam condensates
5. Hydrocyclones discharge
6. Steam condensates
7. Turbines cooling water and steam condensates
8. Boilers blowdown
9. Overflow and backwash water of the water softening plant
10. Floor washing of the oil room
11. }
12. } Wastewaters discharged from various units in the oil room
13. }
14. Overflow from the vacuum dryers
15. Oil trap discharge

A general mass balance of various products generated from a palm oil mill plant is shown in Figure 2.5. It is seen that of the 100 tons fresh fruit bunches (FFB) processed, about 21 tons of palm oil and 6 tons of palm kernel will be produced. Other miscellaneous by-products can be used as animal feed, fertilizer, and boiler fuel.

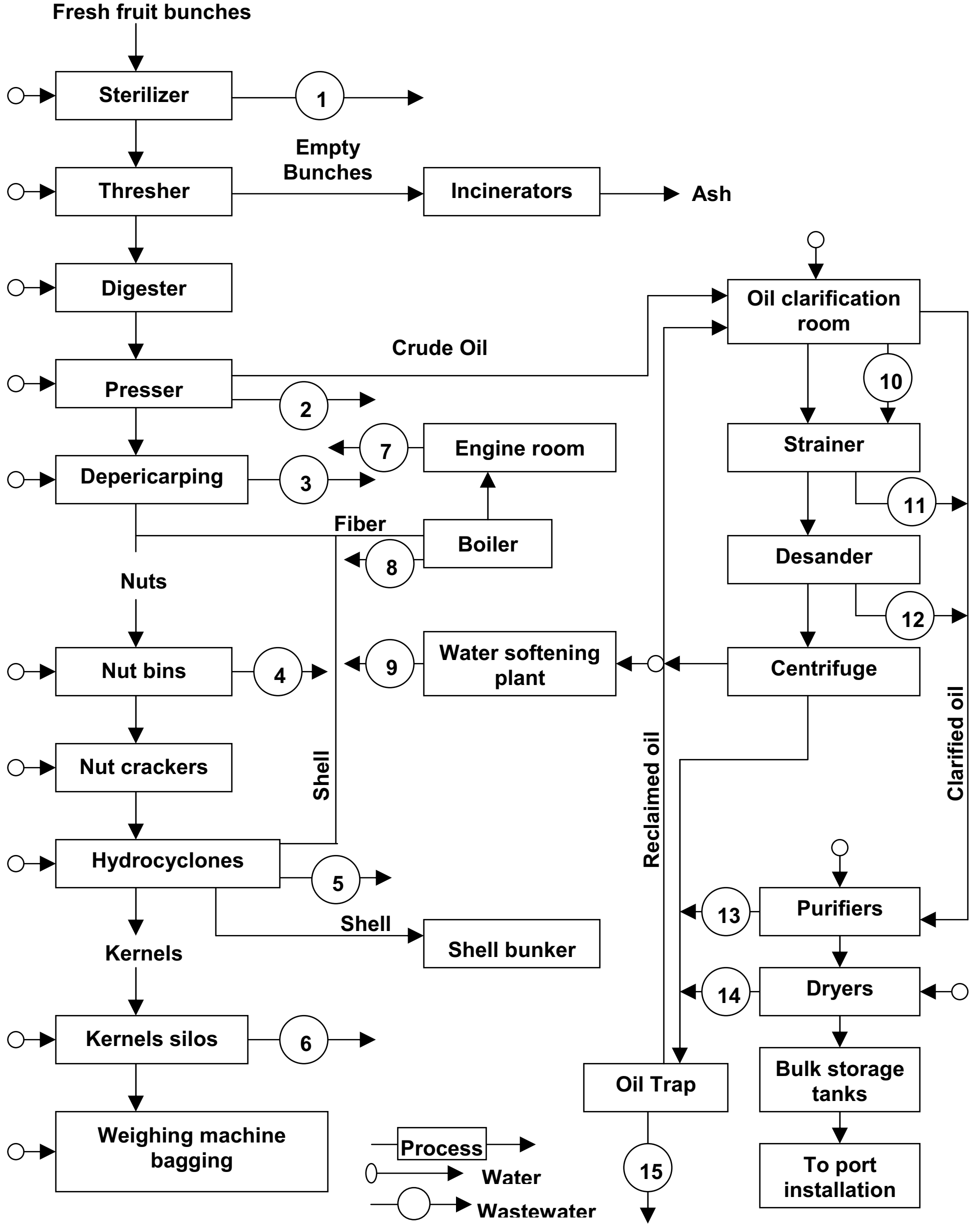

Figure 2.4 General process diagram of a palm oil mill

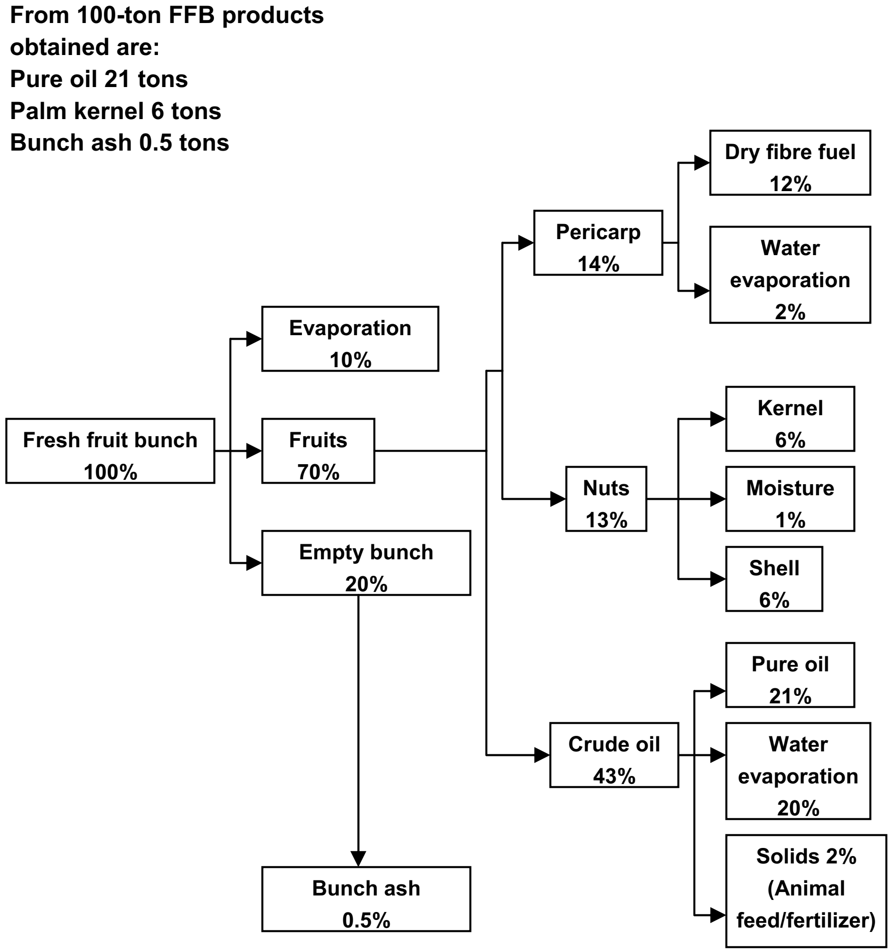

Figure 2.5 Product mass balance of a typical palm oil mill (Muttamara *et al.* 1987)

Palm oil mill wastewater characteristics

Thanh *et al.* (1980) conducted a study on wastewater characteristics of 4 palm oil mills in Malaysia and Thailand. The data of wastewater flows per ton of FFB processed were classified into 50, 70, 80 and 90 percentiles. Table 2.11 shows the percentiles of wastewater flows in m^3 per ton of FFB measured at some sampling stations of the palm oil mills. The characteristics of these wastewaters at 50 percentile values are given in Table 2.12.

Table 2.11 Probability of wastewater flows per ton of FFB processed at different measuring stations of palm oil mills (Thanh *et al.* 1980)

		Flow in m^3/ton FFB (m^3/hour)			
Palm oil mill	Measuring station (see Figure 2.4)	50 Percentile*	70 Percentile*	80 Percentile*	90 Percentile*
Plant A (Malaysia)	1. Oil clarification room	1.04(22.0)	1.14(24.8)	1.21(26.5)	1.31(29.0)
	2. Boiler house and hydrocyclones	0.49(10.5)	0.57(12.5)	0.62(13.8)	0.70(16.0)
	3. Sterilizer building and press station	0.76(15.8)	0.84(17.5)	0.89(18.8)	0.96(20.6)
	4. Combined flow (1+2+3)	2.32(47.0)	2.50 (49.8)	2.60 (51.5)	2.75(54.0)
Plant B (Malaysia)	1. Oil clarification room	1.25(15.5)	1.50 (18.0)	1.68 (19.5)	1.94(22.0)
	2. Boiler house, sterilizer building and hydrocyclones	1.90(21.0)	2.21(23.7)	2.43(25.7)	2.80(28.5)
	3. Combined flow (1+2)	3.23(37.0)	3.72(42.0)	4.10(46.0)	4.60(51.0)
Plant C (Malaysia)	1. Sterilizer building	0.11(2.2)	0.15(2.7)	0.17(3.1)	0.22(3.8)
	2. Oil clarification room	1.30(22.5)	1.60(27.0)	1.83(31.0)	2.21(36.0)
	3. Boiler house	0.52(8.7)	0.61(10.2)	0.67(11.2)	0.76(13.0)
	4. Hydrocyclones	0.27(4.7)	0.34(5.9)	0.38(5.8)	0.45(6.5)
	5. Combined flow (1+2+3)	2.25(36.0)	2.60(41.5)	2.85(45.0)	.25(50.0)
Plant D (Thailand)	1. Oil clarification room	0.89(6.1)	1.01(8.0)	1.09(9.2)	1.11(11.8)
	2. Sterilizer building and oil clarification room	1.09(8.9)	1.21(10.5)	1.29(12.0)	1.39(13.0)
	3. Miscellaneous sources	0.64(4.9)	0.80(5.9)	0.87(6.5)	1.00(7.8)
	4. Combined flow (1+2+3)	1.73(13.8)	2.01(16.4)	2.16(18.5)	2.39(20.8)

*If a 50 percentile flow is used in the design of wastewater treatment facility, it means that 50% of the time the flow of that particular waste stream will be equal or less than the stated figures.

It appears from the above data that wastewaters from the oil clarification room and sterilizer building are the most concentrated, containing high concentrations of COD, BOD, solids and oil & grease. Palm oil mill wastewaters generally have pH below 5 while their temperature can range from 30 to 70°C. The C/N ratios are higher than the optimum value of 30/1, suggesting that some N needs to be added to the wastewater before being treated by biological means.

The main solid wastes produced from palm oil milling are nuts, fibres and shells. The nuts are processed to make kernels, and fibres and shells are used as boiler fuel as explained earlier. Palm oil can be used for cooking and heating. The production of bio diesel using palm oil as a raw material is done in some countries, but depending on local situations, detailed cost-benefit analysis of this practice needs to be carried out to avoid the impacts as stated in section 4.7.1.

2.3.3 Sugar cane industry

Raw sugar cane manufacturing process

A flow diagram of the sugar cane manufacturing process is shown in Figure 2.6. The first step in raw sugar processing is juice extraction carried out by crushing the cane between a series of rollers under pressure. To aid in the extraction of the juice, sprays of water or thin juice are directed on the blanket of bagasse (fibrous part of the cane) as it emerges from each mill unit to leach out sugar. The final bagasse from the last roller contains the unextracted sugar, the woody fiber, and 40-50% water. This is used as fuel or as material for wallboard and paper manufacture.

The extracted juice is acidic, turbid, and dark green in color. It is treated with chemicals, such as lime, sulfur dioxide, carbon dioxide and phosphate, and heated for clarification. This treatment has the effect of precipitating suspended solids and some impurities and color removal, which are allowed to settle, and the clear juice is then filtered through vacuum filters. The filter press juice returns to the clarification process or goes directly to clarified juice. The press cake is discarded or returned to the fields as fertilizer.

Table 2.12 Fifty percentile values of palm oil wastewater characteristics at different sampling stations (all values are in mg/L, except pH which is dimensionless and temperature is in ºC) (Thanh *et al.* 1980)

Palm oil mill	Measuring station	COD	BOD[a]	BOD[a]/COD	TS	SS	Total P	Total N	Oil and grease	pH	Temperature (ºC)
Plant A (Malaysia)	Oil clarification room	64000	30000	0.47	45000	28000	285	490	18500	4.0-4.3	46-77
	Boiler house and hydrocyclones	1860	1050	0.56	1300	850	20.5	14.5	800	4.7-5.9	30-65
	Sterilizer building and press station	10300	5500	0.53	6000	1250	42	60	1100	4.3-4.7	32-77
	Combined flow	28500	14000	0.49	23000	10000	163	265	9600	4.3-4.7	32-75
Plant B (Malaysia)	Oil clarification room	4500	16800	0.37	31000	20000	230	450	11500	3.9-4.8	36-53
	Boiler house, sterilizer building and hydrocyclones	2800	1600	0.57	2180	680	28	39	-	4.9-6.6	30-51
	Combined flow ((1+2)	18300	10000	0.55	15500	7500	135	230	8200	4.1-6.3	30-51
Plant D (Thailand)	Sterilizer building and clarification room	61000	28500	0.46	47500	31000	330	720	86000	4.5-4.9	45-49
	Miscellaneous sources	750	460	0.61	840	360	73	15	180	5.6-7.1	31-33

[a] For plant in Malaysia, BOD was measured at 30ºC for 3 days. For plants in Thailand, BOD was measured at 20ºC for 5 days

The clarified juice contains approximately 88% water. Two-thirds of this water is evaporated in vacuum multiple-effect evaporators. Crystallization takes place in a single-effect vacuum pan where the syrup is evaporated until saturated with sugar. It is at this point that the sugar first appears as fine crystals, which are then built up to the size required for the final product. The mixture of crystals and syrup is then concentrated to a dense mass (massecuite) and the contents of the pan are discharged into a mixer or crystallizer.

The massecuite from the mixer or crystallizer is drawn into revolving machines called centrifugals. The sugar crystals are retained and the mother liquor, molasses, passes through. The final molasses or blackstrap is a heavy viscous material containing approximately one-third reducing sugars, and the remainder ash, organic non-sugars, and water. It may be used as cattle feed or as a raw material for distilleries, to produce ethanol.

Sugar industry wastewater effluents

The sugar industry uses large amounts of water, mainly for cane washing, condensing of vapor, boiler feed water, and other miscellaneous uses. Sources of wastewater and sludge generation during the manufacturing of sugar are given in Figure 2.6. There are air emissions from the sugar manufacturing process which include a variety of pollutants such as particulates, SO_x, NO_x, CO, and hydrocarbons; these pollutants have to be removed to the required air emission standards set by the appropriate regulatory agency.

Table 2.13 Wastewater characteristics of Crescent Sugar Mills, Pakistan (Qureshi 1977)

Characteristics	Range	Fifty percentile	Ninety percentile
pH	6.7-10.0	8.15	9.11
Alkalinity	260-490	370	494
Total solids	4,520-10,790	6,500	10,300
Fixed solids	1,850-6,150	4,000	6,100
Volatile solids	1,825-4,600	2,700	4,500
COD	607-3,680	2,030	3,500
Nitrogen	15-50	33	-
Phosphorus	6.7-11.25	9.25	-

All values are in mg/L, except pH

The characteristics of wastewater from a sugar mill in Pakistan are given in Table 2.13. Its pH varied from 6.7 to 10 and the COD range was 600 - 3,700 mg/L. The wastewater contained rather high solid concentrations in which the ranges of total solids and volatile solids were 4520 - 10790 and 1820 - 4600 mg/L, respectively. Wastewater data from a sugar mill in U.S.A. are also given in Table

2.14, which indicate relatively low N contents, similar to the characteristics of tapioca and palm oil wastewaters (Tables 2.10 and 2.11).

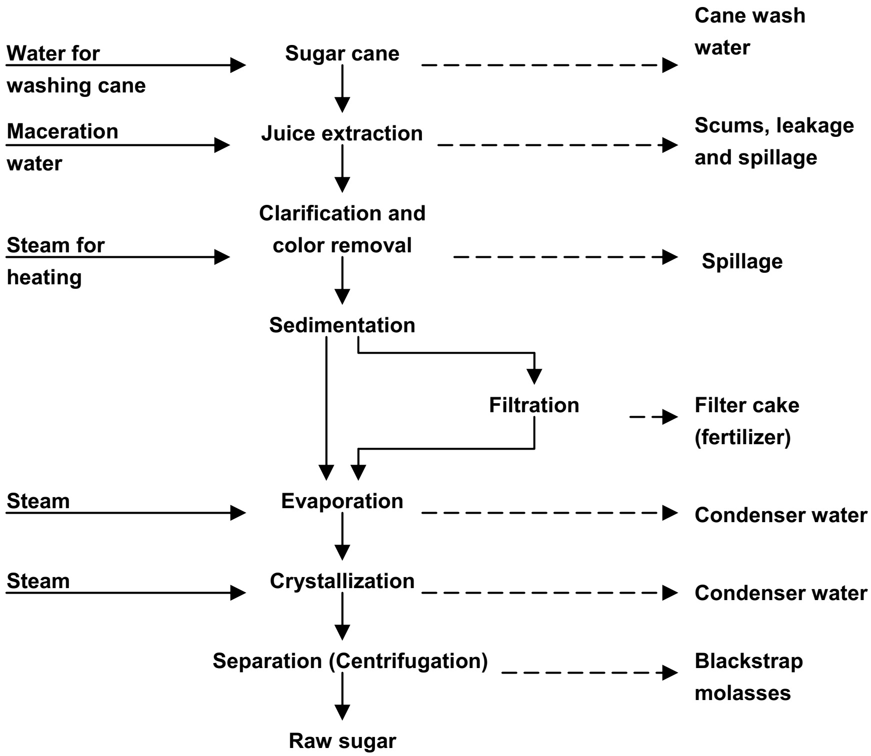

Figure 2.6 Diagrammatic flow sheet of the process of raw sugar manufacture (adapted from Meade and Chen 1977)

2.3.4 Brewing industry

The brewing process

The principal stages in brewing are mashing, boiling and fermentation with subsequent packaging into bottles and casks followed by cooling, clarification and pasteurization.

Table 2.14 Wastewater characteristics of a sugar mill plant in U.S.A. (Oswald *et al.* 1973)

Parameter	**Units**	**Value**
Total nitrogen (N)	mg/L	16.4
Chlorides	mg/L	400[a]
Sulfate	mg/L	210
Alkalinity ($CaCO_3$)	mg/L	538.0[b]
Phosphate (P)	mg/L	3.4
Potassium	mg/L	88.0[c]
BOD_5 (unfiltered)	mg/L	930
COD (unfiltered)	mg/L	1600
Suspended solids	mg/L	1015
Dissolved solids	mg/L	2209
Total solids	mg/L	3224
Sugar	mg/L	1.25
Dissolved oxygen	mg/L	0
pH	-	7.1

[a] Based on specific conductivity, [b] By difference, [c] Single values

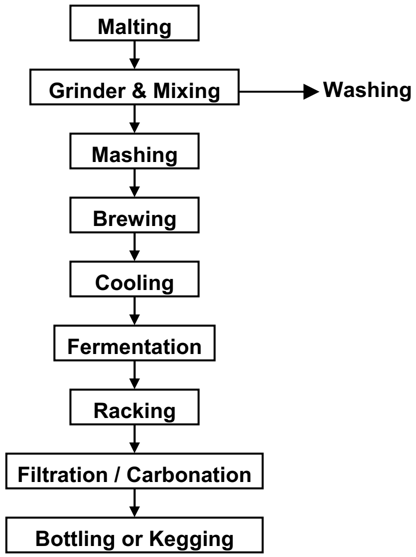

Figure 2.7 Brewing process

During mashing, the mixture of finely ground malt and hot water undergoes enzymatic changes whereby the starch is converted into sugar and dextrins and the protein into amino acids and polypeptides. The soluble product from mashing is known as sweet wort and this is subsequently boiled with hops in a metal vessel. Boiling destroys the enzymes and, at the same time, extracts resins from the hops to give bittering effect. The wort then goes to a cooling process in the cool-ship, yeast is added and during the resultant fermentation, the sugars present are converted into alcohol and CO_2. The nitrogenous material and phosphates in the wort are also utilised by the yeast for growth and fermentation. The beer is stored in lager tanks for some period and filtered and pasteurized before being bottled or canned. A schematic diagram of this brewing process is given in Figure 2.7.

Sources of wastewaters and characteristics

The sources of wastewaters that contain very high amounts of suspended and dissolved solids are: washing from cool ships, lager tanks and fermentation tanks. These wastewaters contain excessive amounts of beer, malt and yeast which possess a very high COD, sometimes as high as 20,000 mg/L, amounting to about 10% of the total waste discharged. Brewery wastewaters normally have an amber color and a rich grainy smell of malt.

Brewery wastewaters have been found to be highly contaminated with soluble organics, low in nutrients and pH, and they have a high temperature (Table 2.15). The COD content can vary from as much as 24,000 mg/L to as little as 6,000 mg/L. The ratio of BOD_5: COD varies between 0.2 and 0.9.

2.3.5 Slaughterhouse industry

This section will describe waste generation from the abattoirs, meat processing plants and poultry processing plants.

Abattoirs (Griffiths 1981)

Lairage / stockyard

Lair refers to animals' lying-place or cages whose wastes comprise mainly of dung and urine - contaminated straw. Straw is separated by a conventional trap and the effluent is fairly weak due to frequent washing down. This effluent is not usually kept separate unless fat is to be recovered from other effluents.

Table 2.16 shows the analysis of wastes from one Chicago stockyard. Another study of these same wastes showed a volume of 623,000 gallons (165 m^3) per day for a 27 acre (11 ha) section of the yard and an average BOD_5 of 100 mg/L (U.S.PHS 1943).

Table 2.15 Characteristics of brewery wastewater (Tantideeravit 1975)

BOD_5 (mg/L)	1800
COD (mg/L)	3100
Total solids (mg/L)	1750
Suspended solids (mg/L)	800
pH	7.5
Alkalinity (mg/L as $CaCO_3$)	160

Table 2.16 Characteristics of stockyard wastewater (U.S.PHS 1943)

Total suspended solids (mg/L)	170
Volatile suspended solids (mg/L)	13
Organic nitrogen (mg/L)	11
Ammonia nitrogen (mg/L)	8
BOD_5 (mg/L)	60

Slaughter: bleeding and carcass separation

Figure 2.8 is a schematic diagram of a slaughter house operation. After killing, the carcasses are bled, the hide is stripped, the abdominal mass is removed and the carcass is split into smaller pieces. At some stage washing takes place which gives rise to dirt, dung, grit, etc., in the effluent.

Blood is normally kept separate to reduce the polluting load in the effluent and because it can be a valuable by-product. The abdominal mass is removed and sorted for collection by the pharmaceutical and by-products industries.

The paunch (stomach) is removed, and it is important to keep the contents out of the normal effluent stream (to simplify subsequent treatment). The contents, partly digested food, are handled separately; they are best kept as dry as possible and disposed of on land as fertilizer.

The cutting down of the carcass involves blood, bone dust, tissue and fat contaminating the wash water, some of which can be caught in traps, but this is the main pollutant which has to be dealt with.

Meat processing (Griffiths 1981)

Meat processing plants are completely different from abattoirs. There is no paunching, no blood, no gut; but there is a lot more meat and fat wastes plus all sorts of additives, e.g. pastry, soya, sauces, spices, preservatives, colorings, etc.

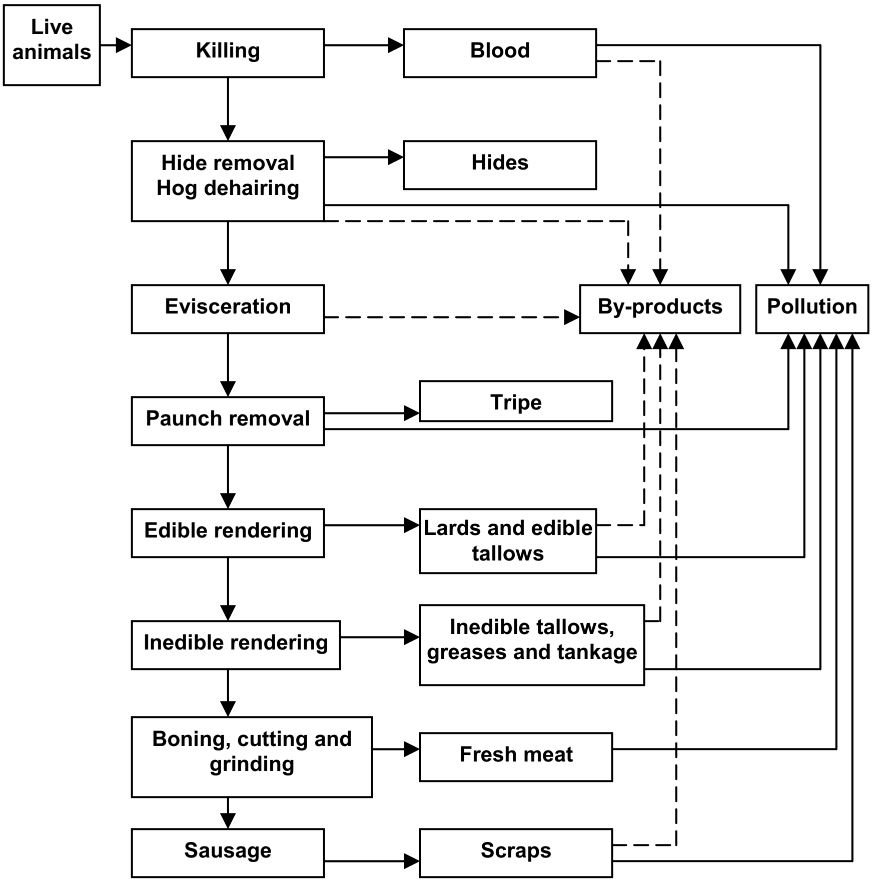

Figure 2.8 Fundamental processes in a slaughterhouse (Nemerow 1971) (© 1971, Addison-Wesley Publishing Co., Reading, Mass)

The major problem is the flow of the effluent stream not being constant. Little water is used whilst production is under way, but when a batch is complete a lot of water is used to wash down. The additives vary and so does production. In order to treat the effluents properly it is necessary in each case to study and to understand the variations in the process and the waste characteristics.

Poultry processing (Griffiths 1981)

Due to the large demand for fowls, poultry processing is now a high volume operation which has developed from its original farmhouse background. The basic procedures for poultry processing are shown in Figure 2.9.

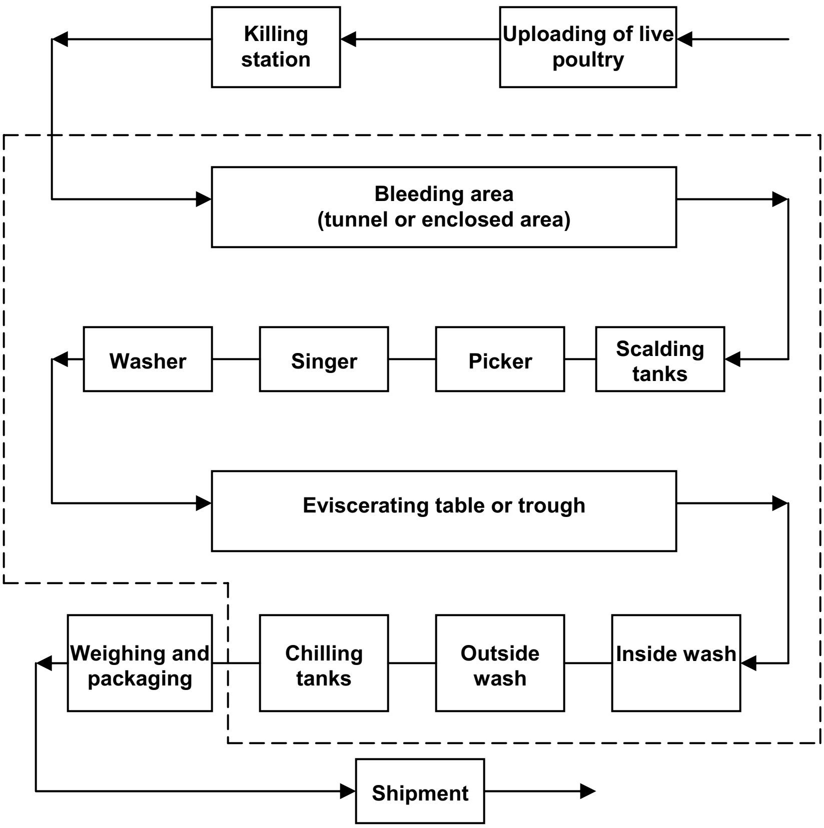

Figure 2.9 Major steps in poultry processing (Nemerow 1971) (© 1971, Addison Wesley Publishing Co., Reading, Mass)

The birds are hung by the feet on a conveyor. They are then killed and bled. The blood is taken away and, if recovered, used for human or pet foods (it is of less value than beef blood).

The next stage is feather plucking. This is done by a series of flaps and flails in a tunnel, under a hot-water spray. There are two ways of disposing of the feathers.

It can be taken away by water in a flume or taken away by a conveyor. The feathers can be reused as a material for mattresses.

Next the heads, feet and innards are removed. The removal of innards is done by hand and they are disposed of by a wet or dry viscera line. In a dry line the innards are removed and taken to a disposal skip by conveyor or by vacuum. In a wet line they are taken by a water flume to be separated later.

The final stages are washing by a fixed amount of water per fowl, then spin chilling and freezing or washing (with the addition of chlorine for disinfection), drying and vacuum sealing.

The following are the possible causes of pollution in the poultry processing effluent:

1. Blood - if not recovered; this has a high BOD_5.
2. Feather water and flume: if a wet flume is used, this can have a high proportion of dissolved or emulsified fats.
3. Wet viscera: requires screening to remove the solid matters.
4. Wash and spin chiller discharge: note that chlorine is introduced in the wash water.

Characteristics of slaughter house and meat-packing wastes

Effluents from slaughter houses and meat-packing houses are usually heavily polluted with solids, floatable matter (fat), blood, manure and a large variety of proteinaceous compounds. The composition depends very much on the type of production and facilities. The main wastes originate from lairage, killing, hide removal or dehairing, paunch handling, rendering, trimming, processing and clean-up operations. The BOD_5 and solids concentrations in the plant effluent depend on in-plant control of water use, by-products recovery, waste separation at the source and plant management.

When considering effluent disposal, the first consideration is water consumption. The range of wastewater production from abattoirs is 5-15 m^3/ton live weight. For the poultry industry a typical discharge lies between 10 and 55 L per bird (Brolls and Broughton 1981).

In terms of BOD_5, typical loads from abattoirs and meat processing are 6-12 kg/ton live weight at UK abattoirs, usually at a concentration of 1,000 - 3,000 mg/L. From poultry packing, the effluent is normally about half the strength of the abattoir wastewater, with a BOD_5 content of 13-23 kg/1,000 birds (Brolls and Broughton 1981)

Some characteristics of slaughter house wastewaters, as reported by Brolls and Broughton (1981), are given in Table 2.17, while those of meat-packing wastes are given in Table 2.18. Table 2.19 shows the wastewater characteristics of a poultry processing plant in Thailand.

Table 2.17 Characteristics of slaughterhouse wastewater (Brolls and Broughton 1981)

Item	Lower range	Upper range
BOD_5 (mg/L)	360 - 1,880	900 - 2,600
Suspended solids (mg/L)	489 - 1,450	600 - 1,800
Organic N (mg/L)	36 - 510	-
Grease (mg/L)	88 - 440	200 - 800
Chlorides (mg/L) as Cl	190 - 5,690	-
pH	6.5 - 8.4	6.1
COD (mg/L)	-	2,000 - 4,900
Flow (L/1000 kg live wt.)		1,690 - 7,920

Table 2.18 Characteristics of meat packing wastewater[a] (Brolls and Broughton 1981)

Item	Average	Range
BOD_5 (mg/L)	1,240	600 - 2,720
COD (mg/L)	2,940	960 - 8,290
Organic N (mg/L)	85	22 - 240
Grease (mg/L)	1,010	250 - 3,000
Suspended solids (mg/L)	1,850	300 - 4,200
Volatile suspended solids (mg/L)	92	80 - 97

[a] Composite samples from 16 plants

Table 2.19 Characteristics of poultry processing wastewater (Visittavanich 1987)

Parameters	Mean	Range
COD (mg/L)	2110	1260 - 3260
BOD_5 (mg/L)	1010	520 - 1740
TKN (mg/L)	150	90 - 200
TS (mg/L)	1940	1290 - 2640
Total P (mg/L)	14	12 - 17
pH	7.1	6.7 - 7.7

2.3.6 Fruit and vegetable industry

Processing operations and waste generation

Unit operation

The processing steps for five typical commodities are outlined in Figure 2.10 for peaches (to exemplify fruits), peas and corn (common vegetables), beets (peeled root crops), and tomato products (pulped commodities). The principal steps where water (or steam) is used and where solid and dissolved residuals are generated are indicated.

The containers of fruits or vegetables are dumped into the first stage washer or flume or onto belts. The products are conveyed by flumes, pipes, belts, elevators, or other conveyors between processing steps. Fluming water, generally reused, and small flows of water to belts, graders, and other equipment for lubrication and sanitation are not noted in the flow diagrams.

Water	Operation	Peas	Corn	Tomato products	Type of waste generated: Solid	Soluble	Soil
	Dry dump	×	×				
→	Water dump			×	●		
	Air cleaner	×	×		●	●	●
	Trash eliminator				●		
	Husker		×		●		
	Sorting/trimming	×	×	×	●		
→	Washer	×	×	×	●	●	
→	Grader/sizer	×			●	●	●
	Cutter		×		●	●	
→	Peeler/rinse			(×)	●	●	
→	Blancher/rinse	×	(×)		●	●	
	Pulper/finisher			(×)			
	Slicer/dicer				●	●	
→	Evaporator			(×)	●	●[b]	

[a] Operational or alternative operations in ().

[b] Relatively clean water

Figure 2.10 Use of water and generation of wastes in typical unit operations of fruit and vegetable processing (U.S. EPA 1971)

Waste generation by unit operations

Much of the total waste flows from many commodities, especially from citrus, come from relatively clean water used in cooling, condensing, and concentrating. The segregation of this water for reuse is practised to some extent and should become almost universal. Other large waste flows are from washing tomatoes, peeling potatoes, peeling peaches, washing potatoes, cutting corn, cutting and pitting peaches, washing corn, and blanching corn. Large quantities of BOD_5 are generated in those processes. Citrus by-products recovery also generates very large amounts of BOD_5 and SS. Other large sources of SS are peeling potatoes, cutting corn, and washing tomatoes.

Peeling: Table 2.20 shows a summary of estimated pollution loads in the effluent from peeling fruits and vegetables reported by various investigators. Peel wastes comprise a high percentage of the total pollution loads in the effluent of fruit and vegetable plants.

Blanching: Table 2.21 shows examples of losses from vegetables during blanching expressed in BOD_5, COD, and SS. The volume of effluent from blanchers is generally relatively small, but the concentrations of suspended and total solids can be high. These wastewaters contain a high organic content (in terms of BOD_5 and COD) which can be treated or recycled by biological processes.

2.4 POLLUTION CAUSED BY HUMAN WASTES AND OTHER WASTEWATERS

Because human, animal and agricultural wastes are organic in nature, when being discharged into a stream or lake, they will serve as food for heterotrophic bacteria. Bacterial reactions will decompose the organic compounds to simple, inorganic end-products with the production of energy for cell synthesis as shown in Equations 2.1 and 2.2 (Metcalf and Eddy Inc. 2003):

Oxidation or dissimilatory process

$$\text{(COHNS)} + O_2 + \text{aerobic bacteria} \rightarrow CO_2 + NH_3 + \text{other end products} + \text{energy} \quad (2.1)$$

Synthesis or assimilatory process

$$\text{(COHNS)} + O_2 + \text{aerobic bacteria} + \text{energy} \rightarrow \underset{\text{(new bacterial cells)}}{C_5H_7O_2N} \quad (2.2)$$

Table 2.20 Characteristics of wastewater from peeling fruits and vegetables [a] (U.S.EPA 1971)

	BOD_5		SS
Product	**kg/ton**	**% of plant waste stream**	**Rate**
Beets (blancher/peeler)	88	84	100 kg/hr
Peaches (rinse after peeling)		40	5 kg/ton
Peaches	27(COD)		5 kg/ton
Peaches	4-6		2.5-4 kg/ton
Potatoes (peeler)	9		41 kg/ton
Potatoes	17-36		34-49 kg/ton
Potatoes (peeler chips)	1		2 kg/ton
Potatoes (peeler/ dehydration)	9		41 kg/ton
Potatoes	15		
Potatoes (lye peel)	84	89	
Potatoes (dry caustic peel)	12	80	
Potatoes (lye peel)	171		
Potatoes (infra red peel)	119		
Potatoes (steam peel)	118		
Potatoes (infra red peel)	91		
Peach/tomato (flume after peel)		1	383 mg/L
Peach/tomato (rinse after peel)		19	1230 mg/L
Peach/tomato (rinse after peel)		20	
Tomato (lye peel)		39	
Tomato (lye peel)		35	

[a] Kilograms of BOD_5 or suspended solids per ton of raw product, or per hour of operation

Under anaerobic conditions (i.e. in the absence of oxygen), anaerobic bacteria will decompose the organic matter as follows:

$$(COHNS) + \text{anaerobic bacteria} \rightarrow CO_2 + H_2S + NH_3 + CH_4 + \text{other end products} + \text{energy} \qquad (2.3)$$

Table 2.21 Pollution loads in effluents from water blanching of vegetables[a] (U.S.EPA 1971)

Vegetable	Effluent flow (L/hr)	BOD_5 (kg/ton)	COD (kg/ton)	SS (kg/ton)
Beets (and peelers)	3,013	88(85)[b]	147(83)	109(55)
Carrots (and peelers)	1,937	44(65)	90(67)	153(64)
Corn	523	11.2(16)	14(18)	3(12)
Peas	294	3,500 ppm in effluent		
Potatoes	580	24	26	21
Potatoes (and peelers)	2,118	84(89)	127(86)	82(37)

[a] BOD_5, COD, and SS in kg per ton of raw product except as noted
[b] Percent of total effluent pollution load in ().

$$(COHNS) + \text{anaerobic bacteria} + \text{energy} \rightarrow \underset{\text{(new bacterial cells)}}{C_5H_7O_2N} \qquad (2.4)$$

Note: $C_5H_7O_2N$ is a common chemical formula used to represent bacterial cells.

In the absence of organic matter, the bacteria will undergo endogenous respiration or self-oxidation, using its own cell tissue as substrate:

$$C_5H_7O_2N + 5O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O + \text{energy} \qquad (2.5)$$

The compounds CO_2 and NH_3 are nutrients for algae. With sufficient sunlight, algal photosynthesis will occur (Oswald and Gotaas 1955):

$$NH_3 + 7.62CO_2 + 2.53H_2O \xrightarrow[\text{Algae}]{\text{Sunlight}} \underset{\text{(new algal cells)}}{C_{7.62}H_{8.06}O_{2.53}N} + 7.62\,O_2 \qquad (2.6)$$

Another equation to incorporate P compound in the algal photosynthesis is (Oswald 1988):

$$106CO_2 + 236H_2O + 16NH_4^+ + HPO_4^{2-} \xrightarrow[\text{Algae}]{\text{Sunlight}} C_{106}H_{181}O_{45}N_{16}P + 118O_2 + 171H_2O + 14H^+ \qquad (2.7)$$

In a natural water course receiving low organic loading, the oxygen produced in Equation 2.6 can be used by the bacteria in Equations 2.1 and 2.2, and the cycle is repeated. This cycle, called 'algal-bacterial symbiosis', is a natural phenomenon occurring in a water body that receives a low organic loading, and these algal-bacterial reactions are in a state of dynamic equilibrium. Parts of the algal and bacterial cells serve as food for protozoa and some small fishes, which are further consumed by big fishes and finally by man.

The discharge of untreated wastes into a receiving water body will create a biologically unbalanced condition. At high organic loading, the bacteria will require more oxygen for their oxidation and synthesis (Equations 2.1 and 2.2), resulting in the depletion of oxygen in the water body which is detrimental to all aquatic life (Figure 1.3). Although algal photosynthesis produces some oxygen (Equation 2.6), during night time when there is no sunlight algae respire or use oxygen, causing a further depletion of oxygen in the water. Eventually, the water will become anaerobic (without oxygen), dark in color, and only anaerobic microorganisms and certain types of worms can live. Besides this organic pollution, the water body would become very unaesthetic to the nearby inhabitants and would lower the environmental quality of its surrounding areas.

However, knowledge of the pollution effects as cited above has, in turn, been used for the design of technologies and facilities for waste treatment and recycling. For example, the reactions of Equations 2.1 and 2.2 are basically used in the design and operation of aerobic waste treatment facilities such as activated sludge, trickling filtration, and composting. The algal-bacterial symbiosis is the basis for the design of facultative waste stabilization ponds and high-rate algal ponds (for the production of algal protein biomass). Equation 2.3 is the reaction where biogas (CH_4 and CO_2) is produced; application of this basic information to waste recycling is given in Chapters 3 to 9.

2.5 DISEASES ASSOCIATED WITH HUMAN AND ANIMAL WASTES

There are various kinds of enteric microorganisms present in human excreta and animal manure, some of which are pathogenic and some are not. They can be classified into such major groups as bacteria, viruses, protozoa and helminths. Some of the important enteric pathogens commonly found in human excreta and wastewater, the diseases they cause, modes of transmission and geographical distribution are listed in Table 2.22 Feachem *et al.* (1983) estimated the possible outputs of some pathogens in the feces and wastewater of a tropical community as shown in Table 2.23.

Table 2.22 Possible output of selected pathogens in the feces and sewage of a tropical community of 50,000 in a developing country

Pathogen	Prevalence of infection in country (percentage)[a]	Average number of organisms per gram of feces[b]	Total excreted daily per infected person[c]	Total excreted daily by town	Concentration per liter in town sewage[b]
Viruses					
Enteroviruses[d]	5	10^6	10^8	2.5×10^{11}	5,000
Bacteria					
Salmonella spp.	7	10^6	10^8	3.5×10^{11}	7,000
Vibrio cholerae	1	10^6	10^8	5×10^{10}	1,000
Protozoa					
Entamoeba histolytica	30	15×10^4	15×10^6	2.25×10^{11}	4,500
Helminths					
Ascaris lumbricoides	60	10^4[f]	10^6	3×10^{10}	600
Hookworms[g]	40	800[f]	8×10^4	1.6×10^9	32
Schistosoma mansoni	25	40[f]	4×10^3	5×10^7	1

Table 2.22 Possible output of selected pathogens in the feces and sewage of a tropical community of 50,000 in a developing country (continued)

Pathogen	Prevalence of infection in country (percentage)[a]	Average number of organisms per gram of feces[b]	Total excreted daily per infected person[c]	Total excreted daily by town	Concentration per liter in town sewage[b]
Taenia saginata	1	10^4	10^4	5×10^8	10
Trichuris trichiura	60	2×10^3[f]	2×10^5	6×10^9	120

[a] The prevalences given in this column refer to infection and not to morbidity

[b] It must be recognized that the pathogens listed have different abilities to survive outside the host, and that the concentration of some of them will rapidly decline after the feces have been passed. The concentrations of pathogens per liter in the sewage of the town were calculated by assuming that 100 liters of sewage are produced daily per capita, amd that 90 percent of the pathogens do not enter the sewers or are inactivated in the first few minutes after excretion

[c] To calculate this figure it is necessary to estimate a mean fecal weight for those people infected. This must necessarily be the roughest of estimates because of the age-specific fecal weights and the age distribution of infected people in the community. It was assumed that people over 15 years old excrete 150 g daily, and that people under 15 excrete, on average 75 g daily. It was also assumed that two-thirds of all infected people are under 15. This gives a mean fecal weight for infected individuals of 100 g

[d] Includes polio-, echo-, and coxsackieviruses

[e] Includes enterotoxigenic, enteroinvasive, and enteropathogenic *E.coli*

[f] The distribution of egg output from people infected by these helminthes is extremely skewed; a few people excrete very high egg concentrations

[g] *Ancylostoma duodenale* and *Necator americanus*

From Feachem *et al.* 1983; reproduced with permission of the World Bank

Table 2.23 Enteric pathogens in human excreta and wastewater (Gaudy and Gaudy 1980; Feachem *et al.* 1983)

Pathogen	Disease	Transmission[a]	Geographical distribution
Bacteria			
Vibrio cholerae	Cholera	Person → person	Asia, Africa, some parts of Europe
Salmonella typhi	Typhoid fever	Person (or animals)→ person	Worldwide
Shigella dysenteriae and other species	Bacterial dysentery	Person → person	Worldwide
Pathogenic *Escherichia coli*	Diarrhea	Person → person	Worldwide
Virus			
Poliovirus	Poliomyelitis	Person → person	Worldwide
Coxsackievirus (some strains)	Various, including severe respiratory disease, fevers, rashes, paralysis, aseptic meningitis, myocarditis	Person → person	Worldwide
Echovirus	Various, similar to coxsackievirus	Person → person	Worldwide

Table 2.23 Enteric pathogens in human excreta and wastewater (Gaudy and Gaudy 1980; Feachem *et al.* 1983) (continued)

Pathogen	Disease	Transmission[a]	Geographical distribution
Adenovirus	Respiratory and gastrointestinal infections	Person → person	Worldwide
Hepatitis	Infectious hepatitis (liver malfunction), also may affect kidneys and spleen	Person → person	Worldwide
Protozoa			
Giardia lamblia	Diarrhea (intestinal parasite)	Person (or animals) → person	Worldwide
Entamoeba histolytica	Amoebic dysentery, infection of other organs	Person → person	Worldwide
Balantidium coli	Dysentery, intestinal ulcers	Person (animals) → person	Worldwide
Helminths			
Ascaris lumbricoides	Ascariasis (roundworm)	Person → soil → person	Worldwide
Ancylostoma duodenale	Hookworm	Person → soil → person	Mainly in warm, wet climates
Schistosoma	Schistosomiasis or bilharziasis	Person → aquatic snail → person	Africa, Asia, South America

Table 2.23 Enteric pathogens in human excreta and wastewater (Gaudy and Gaudy 1980; Feachem *et al.* 1983) (continued)

Pathogen	Disease	Transmission[a]	Geographical distribution
Clonorchis sinensis	Liver fluke	Person (or animal) → aquatic snail → fish → person	Southeast Asia
Taenia saginata	Beef tapeworm	Person → cow → person	Worldwide
Taenia solium	Pork tapeworm	Person → pig (or person) → person	Worldwide
Trichuris trichiura	Whipworm	Person → soil → person	Worldwide

[a] Transmission mode is generally through the fecal-oral route, i.e. the excreted disease may be ingested by other persons or the excreted disease go through some development stages in the environment (water, soil, or animals) and infect other persons. Some virus diseases may be transmitted by the oral-oral route, e.g. through throat secretion. For some helmintic infections such as *Ancylostoma* and *Schitosoma*, the infective larvae will penetrate the skin of a person directly

Table 2.24 Epidemiological aspects of some of the zoonoses

Disease	Causative organism	Principal animals affected	Geographical distribution	Probable vector or means of spread
1. *Virus diseases*				
Arthropod-borne infections:				
Japanese B encephalitis	Virus	Bird, horses, cattle, pigs	Eastern Asia and East Indies	Various *Culex* mosquitoes
St. Louis encephalitis	Virus	Birds, fowl	North America	Various mosquitoes
South African disease				
Rift Valley fever	Virus	Sheep, goats, cattle, related wild animals	South and central Africa	Various mosquitoes
Wesselsbron fever	Virus	Sheep	South Africa	Various mosquitoes
Middleburg disease	Virus	Sheep	South Africa	Various mosquitoes
Contagiuos ecthyma	Virus	Sheep, goats	Europe and North America	Occupational exposure
Cowpox	Virus	Cattle, horses	Worldwide, especially where small pox exists	Contact exposure

Table 2.24 Epidemiological aspects of some of the zoonoses (continued)

Disease	Causative organism	Principal animals affected	Geographical distribution	Probable vector or means of spread
Pseudo-cowpox	Virus	Cattle	Worldwide	Occupational exposure
Psittacosis-ornithosis	Virus	Birds, related virus found in cattle and cats	Worldwide	Contact and occupational exposure
Foot and mouth disease	Virus	Cattle, pigs, related species	Europe, Asia, Africa, and South America	Contact exposure (humans are quite resistant)
Influenza and parainfluenza	Virus	Pigs rodents	Asia and Europe	Contact exposure
Lymphocytic choriomeningitis	Virus	Rodens pigs, dogs	Worldwide	Virus contaminates food and environment
2. *Rickettsial diseases* Q fever	*Coxiella burnetii*	Sheep, cattle, goats, fowl, wild birds, mammals	Worldwide	Mainly airborne, although milk may be a vehicle and occasionally ticks
3. *Bacterial diseases*				
Anthrax	*Bacillus anthracis*	Cattle, sheep, goats	Worldwide	Occupational exposure, ingestion of contaminated meat
Brucellosis	*Brucella abortus*	Cattle, sheep, goats, pigs	Worldwide	Occupational exposure
	Br. suis *Br. melitensis*			Ingestion of contaminated milk products and other foods

Table 2.24 Epidemiological aspects of some of the zoonoses (continued)

Disease	Causative organism	Principal animals affected	Geographical distribution	Probable vector or means of spread
Bacterial food poisoning	Various bacteria and their toxins including *Salmonella, Staphylococcus,* and *Clostridia*	Cattle, pigs, fowl	Worldwide	Occasionally airborne Ingestion
Colibacillosis	*Escherichia* spp. Arizona group	Cattle, pigs, fowl	Worldwide	Ingestion
Listeriosis	*Listeria monocytogenes*	Rodents, sheep, cattle, pigs	Worldwide	Unknown
Melioidosis	*Pseudomonas pseudomallei*	Rodents, sheep	Asia and North America	Exposure and ingestion
Pasteurellosis	*Pasteurella multocida*	Mammals, birds	Worldwide	Exposure and ingestion
Salmonellosis	*Samonella* spp.	Cattle, pigs, fowl	Worldwide	Ingestion, airborne and contact
Staphylococcus	*Staphylococcus* spp.	Cattle, pigs	Worldwide	Ingestion and contact

Table 2.24 Epidemiological aspects of some of the zoonoses (continued)

Disease	Causative organism	Principal animals affected	Geographical distribution	Probable vector or means of spread
Streptococcus	*Streptococcus* spp.	Cattle, fowl	Worldwide	Ingestion and contact
Tuberculosis	*Mycobacterium tuberculosis*		Worldwide	Ingestion, inhalation and occupational exposure
	var. *bovis*	Cattle		
	var. *hominis*	Monkeys		
	var. *avium*	Fowl		
Vibriosis	*Vibrio fetus*	Cattle, sheep	Europe , North and South America	Unknown

From Steele (1996); reproduced by permission of the Food and Agriculture Organization of the United Nations

It is obvious from these tables that human wastes (excreta and wastewater) are a source of health hazards to the public and are the beginning of the transmission route of many diseases. The engineering profession responsible for the collection, transport, treatment and disposal/reuse of these wastes must be aware of the potential infectivity and transmission of these diseases, so as to be able to ensure that these pathogens do not pose an actual threat to human health. Details of these diseases, their modes of transmission and die-offs can be found in *"Sanitation and Disease"* by Feachem *et al.* (1983).

Animals and their manure can also be sources of disease transmission to human beings. The term "zoonoses" is defined as those diseases and infections which are naturally transmitted between man and other vertebrate animals. There are two groups of zoonoses. In the first group, animals act as hosts alternative to man, for example the protozoon *Balantidium* (Table 2.22). In this case both human excreta and animal manure have to be properly controlled to avoid transmission of the disease. *Taenia* (Table 2.22) is an example of the second group of zoonoses in which the animals (either cow or pig) are the intermediate step in the disease transmission. Inactivation of *Taenia* ova in the feces or consumption of well-cooked beef or pork will prevent the transmission of Taeniasis. Therefore the control of either human excreta or animal manure would be sufficient in controlling the spread of the second group of zoonoses. Some of the zoonoses relating to viral, rickettsial and bacterial diseases are given in Table 2.24, while those relating to protozoan and helminthic infections are shown in Table 2.25.

Table 2.25 Partial list of parasitic zoonoses

Disease in humans	Causative organism	Vertebrate animals principally involved
1. *Protozoa infections*		
Amoebiasis	*Entamoeba histolytica*	Nonhuman primates, dogs
Babesiosis	*Babesia divergens*	Cattle
	Babesia microti	Voles, mice
Balantiduasis	*Balantidium coli*	Swine, rats, nonhuman primates
Giadiasis	*Giardia* spp.	Beavers
Sarcoporidiosis intestinal	*Sarcocystis miesheriana (*syn. *S. suihominis; = Isospora hominis proparte)*	Pigs
	*Sarcocytis hominis (*syn. *S. bovihominis; = Isospora hominis proparte)*	Cattle
Toxoplasmosis[a]	*Toxoplasma gondii*	Cats, mammals, birds

Table 2.25 Partial list of parasitic zoonoses (continued)

Disease in humans	Causative organism	Vertebrate animals principally involved
Trypanosomiasis[a]		
African	*Trypanosoma rhodesiense*	Game animals, cattle
America	*Trypanosoma cruzi*	Dogs, cats, pigs, other small mammals
2. *Helminthic infections*		
Trematode infections:		
Amphistomiasis	*Gastrodiscoides hominis*	Swine
Cercarial dermatitis	Schistosomatids	Birds, mammals
Clonorchiasis[a]	*Clonorchis sinensis*	Dogs, cats, swine, wild mammals, fish
Dicrocoeliasis	*Dicrocoelium dendriticum*	Ruminants
	Dicrocoelium hospes	Ruminants
Fascioliasis	*Fasciola hepatica*	Ruminants
	Fasciola gigantica	Ruminants
Fasciolopsiasis[a]	*Fasciolopsis buski*	Swine, dogs
Heterophyasis and other heterophids	*Heterophyes heterophyes*	Cats, dogs, fish
Metagonimiasis	*Metagonimum yokogawi*	Cats, dogs, fish
Opisthorchiasis[a]	*Opisthorchis felineus*	Cats, dogs
	Opisthorchis viverrini and occasionally other *Opisthorchis* species	Cats, wildlife, fish
Schistosomiasis	*Schistosoma japonicum*[a]	Wild and domestic mammals
	Schistosoma haematobium	Rodents
	Schistosoma mansoni	Baboons, rodents
	Schistosoma mekongi	Dogs, monkeys
	Schistosoma mattheej and occasionally other schistosomes	Cattle, sheep, antelopes
Cestode infections:		
Coenuriasis	*Taenia multiceps*	Sheep, ruminants, pigs
Diphyllobothriasis[a]	*Diphyllobothrium latum*	Fish, carnivores
Taeniasis[a]	*Taenia saginata*	Cattle
Taeniasis-cysticercosis[a]	*Taenia solium*	Swine
Nematode infections:		
Ancylostomiasis	*Ancylostoma ceylanicum* and other *Ancylostoma* species	Dogs
Ascariasis	*Ascaris suum*	Swine
Capillariasis		
Intestinal	*Capillaria philippinensis*	Fish
Dioctophymiasis	*Dioctophyme renale*	Fish, dogs
Gongylonemiasis	*Gongylonema* species	Ruminants, rats

Table 2.25 Partial list of parasitic zoonoses (continued)

Disease in humans	Causative organism	Vertebrate animals principally involved
Mammomonogamiasis	*Mammomonogamum laryngeus*	Ruminants
Strongyloidiasis	*Strongyloides stercoralis*	Dogs, monkeys
	Strongyloides fuelleborni	Dogs, monkeys
Thelaziasis	*Thelazia* species	Dogs, ruminants
Trichinellosis[a]	*Trichinella spiralis* and other *Trichinella* species	Swine, rodents, wild carnivores, marine mammals
Trichostrongyliasis	*Trichostrongylus colubriformus* and other *Trichostrongylus* species	Ruminants

From WHO (1970); reproduced by permission of the World Health Organization, Geneva. This list is not comprehensive and is confined to those diseases in which the animal link in the chain of infection to humans is considered to be important, although not alwaus essential.
[a] Diseases or causative organisms of particular importance over large areas

The detection and identification of pathogenic microorganisms are generally difficult, time-consuming and expensive. For routine analyses or monitoring, fecal indicator microorganisms are the preferred microbes analyzed. An ideal indicator should be non-pathogenic, easily detected and counted, present where fecal pathogens are present but in higher numbers, and a member of the normal flora of the intestinal tract of healthy persons.

Some of the common fecal indicators for bacteria are fecal coliforms, fecal streptococci, *Clostridium perfringens*, and *Pseudomonas aeroginosa*. Bacteriophages or coliphages which use bacteria as their host cells have been employed as indicators for enteric viruses. It should be noted that at present, definite relationships between the die-offs of the indicator microorganisms and those of the pathogenic microorganisms are not well established. For example, in a sludge composting unit, the absence of fecal coliforms does not necessarily mean that other enteric bacteria will be dead. Therefore, appropriate indicator microorganisms should be selected for a specific case or a treatment/reuse method being employed. Because they are the most hardy and resistant of all helminth pathogens, viable *Ascaris* ova have been recommended to be the best pathogen indicator for non-effluent wastes (such as nightsoil, the contents of pit latrines, and septage Feachem *et al.* 1983). Liquid or effluent wastes are normally treated by waste stabilization ponds and/or other conventional waste treatment processes including sedimentation. Under satisfactory operation most helminth ova would be removed by sedimentation, while bacteria and viruses are still carried over with the effluents. In this case the use of indicators for either fecal bacteria or viruses would be appropriate. Methods to enumerate common fecal indicators for bacteria and viruses can be found in *Standard Methods* (APHA, AWWA, WEF 2005). The detection of helminth ova can be conducted according to the procedures outlined in Mara and Cairncross (1989).

Table 2.26 Relative health risks from use of untreated excreta and wastewater in agriculture and aquaculture (IRCWD 1985)

Class of pathogen	**Relative excess frequency of infection or disease**
1. Intestinal nematodes: Ascaris, Trichuris, Ancylostoma, Necator	High
2. Bacterial infections: bacterial diarrheas (e.g. cholera), typhoid.	Lower
3. Viral infections: Viral diarrheas, hepatitis A	Least
4. Trematode and cestode schistosomiasis, clonorchiasis, taeniasis	From high to nil, depending upon the particular excreta use practice and local circumstances

In the design and operation of a waste treatment/recycling system, the engineer/scientist in charge has to ensure that the public health risks are kept to a minimum. Each country or state/province normally develops its own standards of microbiological quality to be used in the disposal or reuses of wastewater and sludge.

A report published by the International Reference Centre for Wastes Disposal (IRCWD 1985) proposed the relative health risks from the use of human excreta and wastewater as shown in Table 2.26. The microbiological quality guidelines for wastewater reuse in agricultural irrigation are recommended as given in Table 2.27, while those for aquacultural use of wastewater and excreta are given in Table 2.28. Because of their relatively high health risks, almost complete removal of the ova of intestinal nematodes is emphasized. The guidelines for restricted irrigation aim to protect the health of agricultural workers who are at high risks from nematode infection, while those for unrestricted irrigation are to protect the health of the consumers of the crops. Fecal coliform concentrations of 1000 and 10000 (geometric mean) no. per 100 mL or less are recommended for wastewater to be used in unrestricted irrigation and aquaculture respectively. Because of the high risks of helminthic disease transmission through aquacultural practices, all helminth eggs present in the organic wastes must be rendered non-viable or removed prior to reuses. In areas where there is a high prevalence or an outbreak of a particular disease, attention should be given to the detection of the infectious agent present in the waste to be recycled, or the waste recycling practice is terminated until the disease is under control.

Table 2.27 Tentative microbiological quality guidelines for treated wastewater reuse in agricultural irrigation[a] (IRCWD 1985).

Reuse process	Intestinal nematodes[b] (arithmetic mean no. of viable eggs per litre)	Fecal coliforms (geometric mean no. per 100 ml)
Restricted irrigation[c]		
Irrigation of trees, industrial crops, fodder crops, fruit trees[d] and pasture[e]	≤ 1	Not applicable[c]
Unrestricted irrigation		
Irrigation of edible crops sports fields, and public park[f]	≤ 1	≤ 1000[g]

[a] In specific cases, local epidemiological, socio-cultural, and hydrogeological factors should be taken into account, and these guidelines modified accordingly.

[b] *Ascaris*, *Trichuris* and hookworms.

[c] A minimum degree of treatment equivalent to at least a 1-day anaerobic pond followed by a 5-day facultative pond or its equivalent is required in all cases.

[d] Irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground.

[e] Irrigation should cease two weeks before animals are allowed to graze.

[f] Local epidemiological factors may require a more stringent standard for public lawns, especially hotel lawns in tourist areas.

[g] When edible crops are always consumed well-cooked, this recommendation may be less stringent.

Since the organic wastes described in sections 2.1, 2.2 and 2.3 would normally contain low concentrations of heavy metals, the health risks with respect to heavy metal contamination resulting from the practice of organic waste recycling should not be of a great concern.

However, there is a possibility of accumulation of heavy metals (even though at trace concentrations) in the biological food chain and in soils receiving wastewater and sludge for a long period of time. This long-term accumulation of heavy metals can lead to a problem of bio-magnification where organisms in the upper part of the food chain (e.g. animals or human beings) that feed on the contaminated crops could have heavy metal concentrations several times greater than those present in the soil or crops.

Information about standards or guidelines of heavy metal concentrations in wastewater and sludge to be reused in agriculture or aquaculture are available for most developed countries in North America and Europe; this information will be referred to in Chapters 8 and 9 (Land Treatment of Wastewater and Sludge, respectively).

Table 2.28 Tentative microbiological quality criteria for the aquacultural use of wastewater and excreta (Mara and Caincross 1989)

Reuse process	Viable trematode eggs[a] (arithemetic mean number per liter or kg)	Fecal coliforms (geometric mean number per 100 mL or per 100 g)[b]
Fish culture	0	$< 10^4$
Aquatic macrophyte culture	0	$< 10^4$

[a] *Clonorchis, Fasciolopsis, and Schistosoma.* Consideration should be given to this guideline only in endemic area

[b] This guideline assumes that there is a one $\log_{10}$ unit reduction in fecal coliforms occurring in the pond, so that in-pond concentrations are <1,000 per 100 mL. If consideration of pond temperature and retention time indicates that a higher reduction can be achieved, the guideline may be relaxed accordingly.

2.6 CLEANER PRODUCTION (CP)

The rapid population growth (Figure 1.1) will place more demand on the agricultural and agro-industrial sectors (sections 2.2 and 2.3) to produce more food for human consumption. Accordingly, the extent of agricultural and agro-industrial practices in this decade will have to expand and becoming more intensive, resulting in more generation of organic wastes which need to be properly handled. This section will describe the principles of cleaner production and their application to achieve waste minimization, pollution control and cost saving.

Cleaner production (CP) is the continuous application of an integrated preventive environmental strategy to processes, products and services to increase overall efficiency. CP can be applied to the processes used in any industry, to products themselves and to various services to the society. For example, for an agro-industrial process, CP results from one or a combination of conserving raw materials, water and energy; eliminating toxic and hazardous raw materials and reducing the quantity and toxicity of all emissions and wastes at sources during the production process. For an agro-industrial product, CP aims to reduce the environmental, health and safety impacts of the products over its entire life cycles, from raw material extraction, through manufacturing and use, to the ultimate disposal of the product. For services, CP implies incorporating environmental concerns into designing and delivering services (UNEP 2001).

Table 2.29 shows a comparison between conventional and cleaner production for an industry. It is apparent from this table that industries that practice CP could achieve the following benefits:

- Improved products and processes
- Saving on raw materials and energy, and production costs
- Increased competitiveness through the use of new and improved technologies
- Reducing needs for more environmental regulations
- Reducing risks from on and off site treatment, storage and disposal of toxic and other kinds of wastes
- Improved health and safety of employees
- Improved staff morale, leading to better productivity
- Improving the industry's public image, and
- Reducing the cost of end-of-pipe solutions

Table 2.29 Comparison between conventional and cleaner production (UNEP 2001)

Considering point	Conventional production	Cleaner production
Process design	not designed for waste prevention	designed for minimum waste or zero waste
Plant lay-out design	not designed	designed to minimize motion in work
Selection of raw materials	use cheapest raw materials	use raw materials less effect on environments
By product	no use of by products, considering in term of waste	use of by-product
Product	less concern on environments	concern impact to environments at the end of their life
Treatment	end-of-pipe pollution technology	pollution control technology

However, there are some limitations to the CP approach and operation as listed in Table 2.30. For a CP program to be successful, these limitations, which can vary from industry to industry, have to be understood and resolved by the management and concerned personnel. The four principle steps in the planning and implementation of a CP program as shown in Figure 2.11 are briefly described below:

Table 2.30 Limitations for cleaner production (UNEP 2001)

Types of constraints	Sub categories
Financial	High cost of external capital for investments in industry.
	Lack of funding mechanisms (lending schemes etc) appropriate for cleaner production investments.
	Perception that investments in cleaner production present a high financial risk due to the innovative nature of cleaner production
	Cleaner production not properly valued by credit providers in their evaluation procedures for lending, equity participation.
Economic	Cleaner production investments are not sufficiently cost effective (compared with other investment opportunities), given present resources prices
	Immaturity of the company's internal cost calculation and cost allocation practices
	Immaturity of the company's internal capital budgeting and capital allocation procedures
Policy-related	Insufficient focus on cleaner production in environmental, technology, trade and industry development and strategies.
	Immaturity of the environmental policy framework (including lack of enforcement, etc.)
Organizational	Lack of leadership for environmental affairs
	Perceived management risk related to cleaner production (e.g. no incentives for managers to put their efforts into implementation of cleaner production)
	Immaturity of the environmental management function in the company's operations.
	(General) immaturity of the organization structure of the company and its management and information systems.
	Limited experience with employee involvement and project work
Technical	Absence of a sound operational basis (with well established production practices, maintenance schemes etc.)
	Complexity of cleaner production (e.g. need to undertake comprehensive assessment to engineering small wares for process instrumentation)
	Limited accessibility of equipments supportive to cleaner production (e.g. high quality engineering small wares for process instrumentation)
	Limited accessibility of reliable technical information tailored to the company's needs and assimilative capacities.
Conceptual	Indifference: perception regarding the own role in contributing to environmental improvement
	Narrow interpretation or misunderstanding of the cleaner production concept
	(General) resistance to change

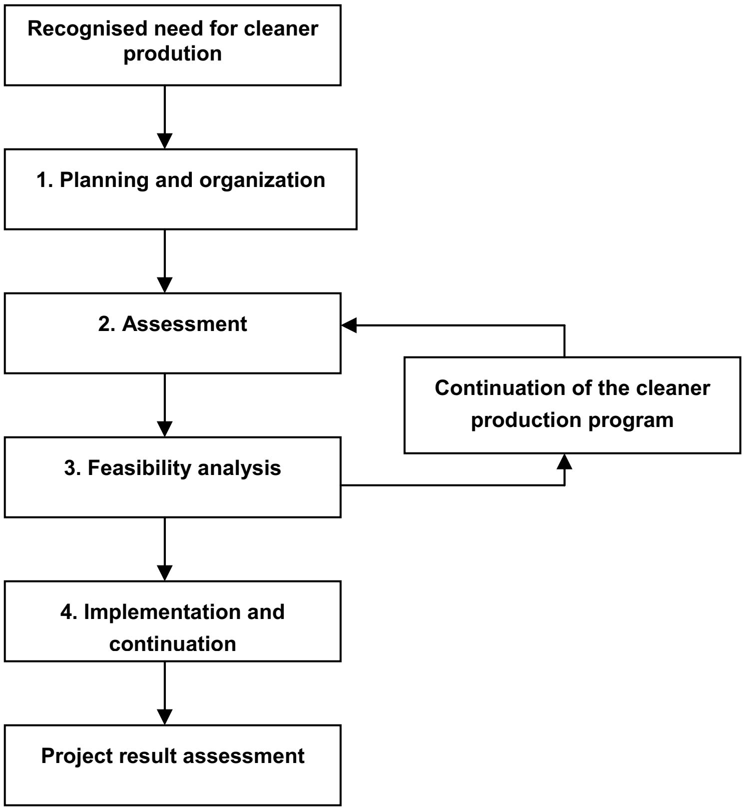

Figure 2.11 Four principle steps of cleaner production

2.6.1 Planning and organization

Planning and organization starts once one or a few persons in the company become interested in cleaner production. A CP assessment can be initiated after a conscious decision has been made by the management to take action. Experiences from a growing number of companies show that the following elements are important for the successful start of a CP program:

Management committee: Plant management has to set the stage for CP activities in order to ensure collaboration and participation. Management committee may be reflected in environmental policy statements; however, the actual behaviour of the management is at least equally important as written statements. A CP project team has to be set up to initiate, co-ordinate and supervise the CP activities.

Employee involvement: Management should set the stage, but whether or not good CP opportunities are found is largely dependent on the collaboration of employees. Employees, in particular those involved in the daily operations and maintenance on the shop-floor usually have good understanding of why wastes and emissions are generated, and are often able to come up with solutions.

Cost awareness: Proper cost information can convince management, as well as employees, that producing cleaner can save or make money. Unfortunately, many companies, in particular small and medium sized enterprises, do not know how much money is wasted. Typically, only costs charged by external waste contractors are taken into consideration. Actual waste costs can be significantly more.

2.6.2 Assessment

During the assessment phase the material balance is studied, and appropriate measures are proposed to reduce or prevent loss of materials. The ideas for options may come from literature search, personal knowledge, discussion with suppliers, examples in other companies and specialized data bases. Brainstorming is an indispensable tool to ensure creative intellectual environment to think of all possibilities.

A key assessment objective is to reduce waste generation at the source or source reduction which involves such options as: good operating practices, technology changes and input material changes. A brief description of source reduction and the related options are given below.

Source reduction refers to any practices which reduce the amount of any pollutant or contaminant entering any waste stream of otherwise released into the environment prior to recycling, treatment or disposal (Holmes *et al.* 1993).

By avoiding the generation of wastes, source reduction eliminates the problems associated with the handling and disposal of wastes. A wide variety of facilities can adopt procedures to minimize the quantity of waste generated. Many source reduction options involve a change in procedural and organizational activities, rather than a change in technology. For this reason, these options tend to affect the managerial aspect of production and usually do not demand large capital and time investments.

Figure 2.12 shows the various options of source reduction which can be categorized as good operating practices, changes in technology, input materials or products.

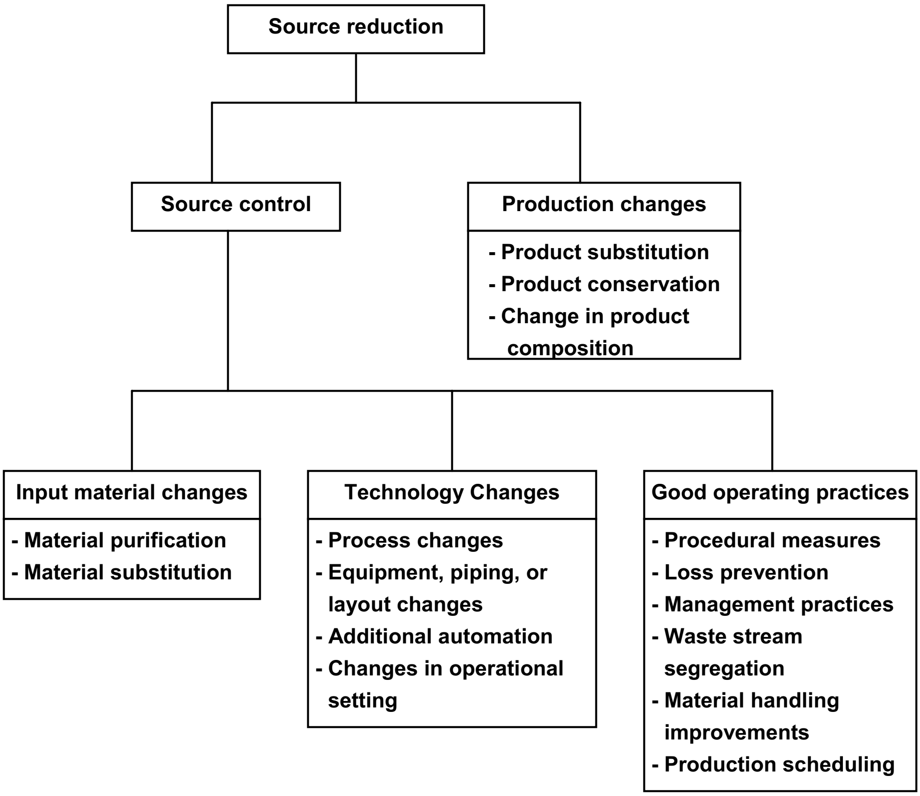

Figure 2.12 Source reduction (U.S. EPA 1988)

Good operating practices

Good operating practices are procedural, administrative or institutional measures that an industry can use to minimize waste. Good operating practices apply to the human aspects of manufacturing operations which can often be implemented with little cost and, therefore, have a high return on investment. Good operating practices include the following (U.S. EPA 1998):

- waste minimization programs;
- management and personnel practices, including employee training, incentives and bonuses, and other program that encourage employees to conscientiously strive to reduce waste;

- materials handling and inventory practices, including programs to reduce loss of input materials due to mishandling, expired shelf life of time sensitive materials;
- loss prevention by avoiding leaks from equipment and spills;
- waste segregation;
- cost accounting practices, including programs to allocate waste treatment and disposal costs directly to the departments or groups that generate waste, rather than charging these costs to general factory overhead accounts; and
- Production scheduling.

Example 2.1

A sausage industry plans to assess the production of its grinding machine (refer to Figure 2.8) by using cleaner production method. Determine the percent loss and percent waste generated from the grinding machine. For input materials, raw meat is 10,000 kg/hr, ingredient is 2,000 kg/hr and water consumption is 3 m^3/ hr. For outputs, ground meat is 8,500 kg/hr and wastewater generated is 5m^3/hr. The densities of water and wastewater are 1,000 kg/m^3 and 1,200 kg/m^3, respectively.

Solution

1. For the inputs:

Raw meat		10,000	kg/hr
Ingredients		2,000	kg/hr
Water consumption	3×1,000=	3,000	kg/hr
Total inputs		15,000	kg/hr

2. For the outputs:

Ground meat		8,500	kg/hr
Wastewater generated	5×1,200=	6,000	kg/hr
Total output		14,500	kg/hr

3. Percent loss and waste generated

$$\text{Percent loss} = \frac{(15{,}000 - 14{,}500)}{15{,}000} \times 100 = \quad 3.30\%$$

$$\text{Percent waste generated} = \frac{6{,}000}{15{,}000} \times 100 = \quad 40.00\%$$

2.6.3 Feasibility analysis

The feasibility analysis has to prove whether each or a combination of the above options are technically and economically feasible and whether they contribute to the environmental improvement. The technically non-feasible options and the options without significant environmental benefits can be eliminated. All remaining options can, in principle, be implemented. Example 2.2 compares financial feasibility of two CP options

Example 2.2

The sausage industry from Example 2.1 needs to reduce the quantity of waste generated by considering two alternatives. For the first alternative, a recovering machine will be set up to recover the small pieces of meat contained in the wastewater back to the grinding process. The density of the wastewater will then be reduced to 1,050 kg/m^3. For the second alternative, the old grinding machine will be replaced by a new one, so the wastewater generated will be reduced to 4m^3/hr (density is 1200 m^3/kg) and ground meat output will be 9,250 kg/hr. The investment costs of the recovering machine and the new grinding machine are \$100 and \$150, respectively. The two machines are assumed to have the same lifetime and the wastewater treatment costs are the same.

Solution

A. For the first alternative which employs a recovering machine

Wastewater generated	5 × 1,050 =	5,250	kg/hr
Small pieces of meat recovered	6,000- 5,250 =	750	kg/hr
Total ground meat	8,500 + 750 =	9,250	kg/hr
Production quanity per investment cost	9,250/100 =	92.5	kg/hr/$

B. For the second alternative which employs a new grinding machine

Wastewater generated	4 × 1,200 =	4,800	kg/hr
Ground meat		9,250	kg/hr
Production quanity per investment cost	9,250/150 =	61.67	kg/hr/$

The first alternative which employs a recovering machine gives higher production quantity per cost than the second alternative. Therefore based on the financial feasibility, the recovering machine should be selected.

Technology changes

Technology changes are oriented toward process and equipment modifications to reduce waste, primarily in a production setting. Technology changes include the following:

1. changes in the production process;
2. equipment, layout, or piping changes;
3. use of automation; and
4. changes in process operating conditions, such as flow rate, temperatures, pressures, and residence times.

Example: Technology changes

The U.S. DA-Magnuson Infrared Antipollution Peeling Process uses infrared energy at 900°C (1,650°F) to condition the surfaces of potatoes treated with strong sodium hydroxide solutions (refer to Figures 2.2 and 2.3). The peel can then be removed mechanically by soft rubber scrubbing rolls rather than by water as is done in conventional caustic peeling. A final spray rinse using low volumes of water removes residual peel fragments and excess sodium hydroxide. Direct comparison of this process with conventional peeling has demonstrated that the strength of the waste discharged has been reduced by 40 percent (Jones 1973).

Input material changes

Input material changes accomplish waste minimization by reducing or eliminating the pollutant materials that enter the production process. Also, changes in input material can be made to avoid the generation of pollutant wastes within the production processes. Input material changes include: (i) material purification; and (ii) material substitution.

Product changes

Product changes are performed by the manufacturer of a product with the intent of reducing waste resulting from a product's use. Product changes include:

1. product substitution;
2. product conservation; and
3. changes in product composition.

2.6.4 Implementation and continuation

To achieve the CP result, the following tasks should be undertaken:

Prepare cleaner production plan: the CP measures are organized according to the expected dates of implementation. Additionally, the person or department with the prime responsibility for the implementation should be identified.

Implement feasible cleaner production measures: The effort needed to implement various cleaner production measures can differ substantially. Simple CP measures (like good housekeeping) can be easily implemented. However, focus should be on complex CP measures, which require a substantial investment (high cost option) and detailed preparation such as planning for equipment installation and funding requirements. The installation of equipment requires supervision in order to safeguard optimal use of the new facilities.

Monitor cleaner production progress: Simple indicators should be used to monitor CP progress and to keep the management as well as other interested parties frequently informed. The choice of the measurement method is crucial. It can be based on the changes in waste (and/or emission) quantities, changes in resource consumption (including energy) or changes in profitability. The evaluation of the monitoring data should include changes in the production output and/or changes in the product mix.

Sustain cleaner production: The ongoing application of the cleaner production concept may require structural changes in the organization and management system of the company. The key areas are: integration into the technical development of the company, proper accountability of waste generation, and employee involvement. Integration into the technical development could include preventive maintenance schedules, integration of environmental criteria (such as energy and resource consumption) in the selection of new equipment, or integration of CP into long term research and development plans. Employee involvement can be achieved by staff education, creation of regular opportunities for two way internal communication and employee reward programs.

The following case studies demonstrate CP activities done at some industries in Thailand, Australia, and U.K.

Case study A: Frozen shrimp industry, Thailand

A frozen shrimp factory in Thailand, having over 4,000 workers and staffs, operates eight hours a day, six days a week. The main products are frozen shrimp and cuttlefish. Ninety percent of the factory products are exported: twenty percent to United States, ten percent to Europe and sixty percent to Asia.

Recently, the frozen shrimp production was found to consume 2,400 tons of shrimp, 980,000 kWh of energy and 78,000 m^3 of water per year. The average annual production was 1,500 tons of frozen shrimp. By adopting available CP technology, such as heat exchanger, insulation and equipment modification, water consumption in the cleaning process was reduced to 55,380 m^3 per year or a 30% reduction, and energy consumption was reduced up to nearly 50%. Good house keeping practices were taken for all parts of the production process (Yolthantham 2002)

Case study B: Birkdale Nursery, Australia

Brikdale Nursery has a reputation of being one of Australia's leading ornamental horticultural businesses. It was one of the first nurseries to achieve ISO certification (ISO 9002: 1994) and was an active participant in the EPA'a Cleaner Production Partnerships Program.

Increased water charges along with an expansion of the nursery meant that Brikdale Nursery faced a hefty water bill. The CP assessment made recommendations to combat excessive water consumption by using alternative water sources and reuse techniques. Brikdale Nursery has two main sources of water: town water (at a cost of about 0.7 $/kL) and dam water (leased on adjacent land for $10,000 per year). The assessment identified two areas where Brikdale Nursery could reduce water use: collection of run-off water for re-use and efficient use of water in the plant propagating area. For the first method, the site has been re-designed to collect run-off for re-use on site. Run-off is collected, screened, disinfected with chlorine and then re-used to water plants in the later stages of development. Approximately 35 to 45 percent of the total water used on the site is now recycled. Water re-use and the use of dam water as an alternative has cut the treated town water bill by a staggering $2,000 per week. For the efficient water use, the plant propagation takes place in an enclosed building monitored for temperature and humidity. This is the only area that uses treated town water, as the young plants have a high level of sensitivity. To reduce water use, overhead fine mist sprinklers and capillary watering systems are now used. The sprinklers are triggered to operate only when the humidity drops below the desired level. Capillary watering, via mats, delivers the required amount of water directly to plant roots. A small amount of additional overhead watering is needed to remove salt from the top of the soil (www.env.gld.gov.au).

Case study C: Waste minimization in the food and drink industry, East Anglia, U.K.

Waste minimization in the food and drink industry leads to many improvements such as energy efficiency, reduction of raw material use, reduction in water consumption and increasing reuse and recycling on site. Such improvements in environmental performance result in the profitability of business.

The East Anglia, U.K., waste minimization in the food and drink industry project demonstrated that waste reduction of 12 % of raw materials can be achieved through good operating practices and this has made a significant contribution to the company profitability by improving yields per unit output and by reducing costs associated with waste disposal. Potentials for further improvements through improving dialogue between producers, retailers and consumers are being studied (Hyde *et al.* 2001)

2.6.5 Waste recycling

A material is "recycled" if it is used, reused, or reclaimed. Recycling through use and/or reuse involves returning waste material either to the original process as a substitute for an input material, or to another process as an input material. Recycling through reclamation is the processing of a waste for recovery of a valuable material or for regeneration. Recycling techniques may be performed on site or at an off-site facility designed to recycle the waste. Recycling of wastes can provide a very cost-effective waste management alternative. This option can help eliminate waste disposal costs, reduce raw material costs, and provide income from salable waste. The technologies described in Chapter 3-9 are mainly for waste recycling purposes.

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2.8 EXERCISES

2.1 You are to visit an agro-based industry or an animal farm and determine the waste quantity and characteristics. Compare the results obtained with the data presented in Chapter 2.

2.2 From the data given in Table 2.1, derive the following information for your hometown:

a) Daily generation of human excreta both in wet weight and in volume, assuming a density of 1.05 kg/L.
b) Daily production of total solids from the excreta.
c) Daily production of total nitrogen from the excreta.
d) Daily production of BOD_5 from the excreta.
e) C/N ratio of the excreta.

2.3 A chicken farm has 5000 laying hens in stock, each with an average live weight (LW) of 1.5 kg. Use the data in Table 2.6 to estimate the following:

a) Daily production of chicken wastes in wet weight.
b) Daily production of total solids from the chicken farm.
c) Daily production of volatile solids.
d) Daily production of total nitrogen.

2.4 Based on the microbiological guidelines given in Tables 2.27 and 2.28, you are to survey a waste recycling project (either in agriculture or aquaculture) and collect the wastewater for analysis of fecal coliform and nematode egg contents.

From the results obtained, discuss the possible health impacts of this waste recycling practice.

2.5 Discuss the extent of waste minimization that is being implemented in your country at the national and local (city) levels.

2.6 You are to visit an agro-industrial factory in your area and with permission of the factory management, observe the factory operation with respect to the "Cleaner Production" principles. List some improvement measures the factory can do towards the cleaner production goals and the benefits to be gained from these improvements measures.

2.7 Find out the common waterborne diseases occurring in your country, determine the causes of the disease transmission and recommend measures to prevent the disease transmission.

2.8 Find out the water quality standards for agricultural and aquacultural reuses in your country and compare with those given in Table 2.27 and 2.28. If not available, discuss whether Table 2.27 and 2.28 can be applied for use in your country.

3

Composting

Haug (1980) defined composting as the biological decomposition and stabilization of organic substrates under conditions which allow development of thermophilic temperatures as a result of biologically produced heat, with a final product sufficiently stable for storage and application to land without adverse environmental effects. Another definition refers composting to a controlled aerobic process carried out by successive microbial populations combining both mesophilic and thermophilic activities, leading to the production of carbon dioxide, water, minerals, and stabilized organic matter (Pereira-Neta, 1987). Generally, composting is applied to solid and semi-solid organic wastes such as nightsoil, sludge, animal manures, agricultural residues, and municipal refuse, whose solid contents are usually higher than 5 %.

Aerobic composting is the decomposition of organic wastes in the presence of oxygen (air); the end-products of biological metabolism are carbon dioxide (CO_2), NH_3, water and heat (similar to Equation 2.1). Anaerobic composting is the decomposition of organic wastes in the absence of oxygen; the end-products are methane (CH_4), CO_2, NH_3 and trace amounts of other gases, and other low-molecular-weight organic acids (Equation 2.3). NH_3 is further oxidized to become nitrate (NO_3^-) by the nitrifying bacteria during the maturation or curing phase. Because it can release more heat energy resulting in a rapid decomposition rate, aerobic composting has been a preferred technology for stabilizing large quantities of organic wastes. Anaerobic composting is a slow process and can produce obnoxious odors originating from the intermediate metabolites such as mercaptans and sulfides. Depending on the methods of operation, anaerobic composting can produce temperatures near to or at thermophilic levels. Because of its simplicity, anaerobic composting has found some applications in many rural areas of developing countries in the stabilization of wastes generated from households and farms.

It should be noted that, in contrast to wastewater treatment, the terms "aerobic" and "anaerobic" for composting have relative meanings. They simply indicate what conditions are predominant in the process. Since the compost materials are heterogeneous and bulky in character, in a compost heap, there always exist "anaerobic" composting, which are few in "aerobic" composting but abundant in "anaerobic" composting; and vice versa. Some composting processes, such as composting pits being practiced in rural China, are aerobic at first and become anaerobic during the later stages of composting period.

Using technology as the key, composting can be classified into 'mechanical' and 'non-mechanical' processes, or 'on-site' and 'off-site' processes. Composting can also be divided with respect to the modes of operation, i.e. batch operation and continuous or semi-continuous operation. These technologies and operational classifications of composting processes will be described in section 3.6. When temperature is the basis, composting can be divided into 'mesophilic' composting (whose temperatures in the compost heap are between 25-40°C) and 'thermophilic' composting (whose temperatures are between 50-65°C).

3.1 OBJECTIVES, BENEFITS AND LIMITATIONS OF COMPOSTING

The main purposes and advantages of composting are classified as follows:

- Waste stabilization. The biological reactions occurring during composting will convert the putrescible forms of organic wastes into stable, mainly inorganic forms which would cause little pollution effects if discharged onto land or into a water course.
- Pathogen inactivation. The waste heat biologically produced during composting can reach a temperature of about 60 °C which is sufficient to inactivate most pathogenic bacteria, viruses and helminthic ova, provided that this temperature is maintained for at least 1 day. Therefore, the composted products can be safely disposed of on land or used as

fertilizers/soil-conditioners. Figure 3.1 shows the influence of time and temperature on die-off of selected pathogens in nightsoil and sludge. The higher the temperature the shorter the time required for pathogen die-off.

- Nutrient and land reclamation. The nutrients (N, P, K) present in the wastes are usually in complex organic forms, which are difficult for the crops to uptake. After composting, these nutrients would be in inorganic forms such as NO_3^- and PO_4^{-3} suitable for crop uptake. The application of composed products as fertilizer to land reduces loss of nutrients through leaching because the inorganic nutrients are mainly in the insoluble forms which are less likely to leach than the soluble forms of the uncomposted wastes. In addition, the soil tilth is improved, thereby permitting better root growth and consequent accessibility to the nutrients (Golueke 1982). The application of compost to unproductive soils would eventually improve the soil quality and the otherwise useless lands can be reclaimed.
- Sludge drying. Human excreta, animal manure and sludge contain about 80-95% water which makes the costs of sludge collection, transportation and disposal expensive. Sludge drying through composting is an alternative in which the waste heat biologically produced will evaporate the water contained in the sludge.

A major drawback of composting concerns the unreliability of the process in providing the expected nutrient concentrations and pathogen die-offs. Because the characteristics of organic wastes can vary greatly from batch to batch, with time, climates, and modes of operation, the properties of the composted products would also vary accordingly. The heterogeneous nature of materials in the compost piles usually causes uneven temperature distribution (except in well-operated compost reactors - see section 3.6), resulting in incomplete inactivation of pathogens present in the composted materials. Other limitations of composting relate to socio-economic factors. For example, the handling of nightsoil during composting can be unappealing, unaesthetic and obnoxious in odor. Most farmers still prefer to use chemical fertilizers because they are relatively not too expensive and, in short term, produce reliable results on crop yields.

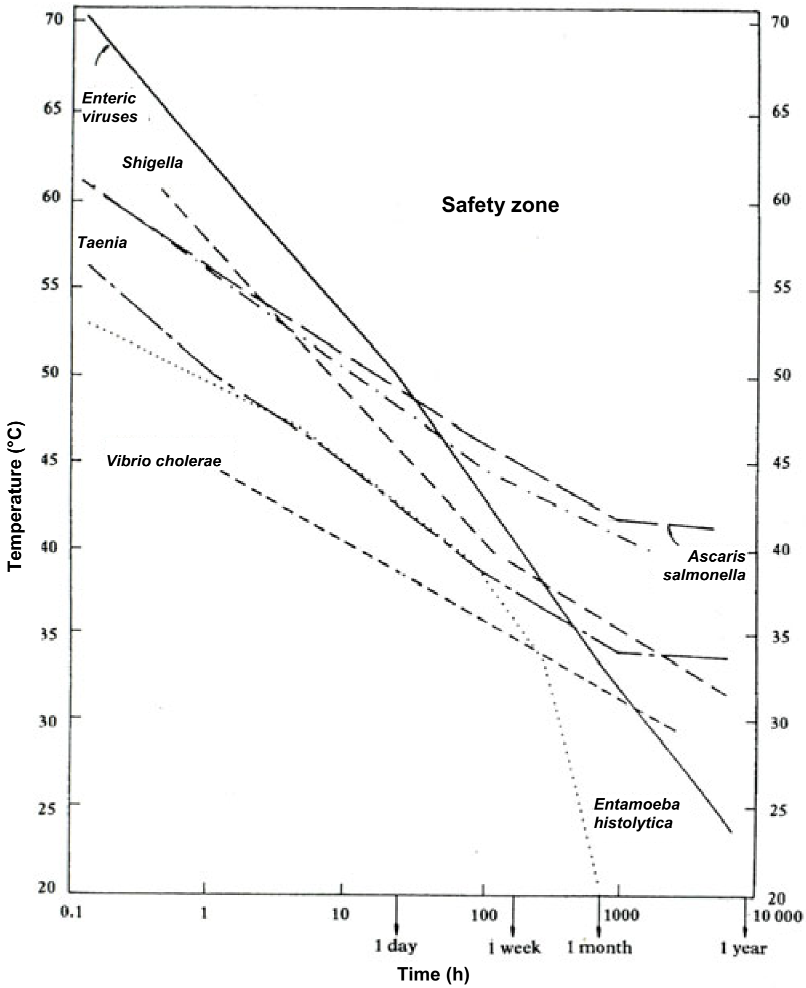

Figure 3.1 Influent of time and temperature on selected pathogens in night soil and sludge (Feachem *et al.* 1983; reproduced by permission of the World Bank). *Note:* The time represents conservative upper boundaries for pathogen death that is, estimates of time-temperature combinations required for pathogen inactivation. A treatment process with time-temperature effect falling within the "safety zone" should be lethal to all excreted pathogens (with the possible exception of hepatitis A virus – not included in the enteric viruses in the figure – at short retention time). Indicated time-temperature requirements are at least: 1 h at ≥ 62°C, 1 day at ≥ 50°C and 1 week at ≥ 46°C

3.2 BIOCHEMICAL REACTIONS

Organic wastes suitable for composting vary from the highly heterogeneous materials present in municipal refuse and sludge to virtually homogeneous wastes from food processing plants. The courses of biochemically breaking down these wastes are very complex, encountering several intermediates and pathways. For examples, the breaking down of proteins includes the following pathways:

Proteins → peptides → amino acids → ammonium compounds → bacterial protoplasm and atmospheric nitrogen or ammonia.

For carbohydrates:

Carbohydrates → simple sugars → organic acids → CO_2 and bacterial protoplasm.

The precise details of the biochemical changes taking place during the complex processes of composting are still lacking. The phases which can be distinguished in the composting processes according to temperature patterns are (Figure 3.2):

- Latent phase, which corresponds to the time necessary for the microorganisms to acclimatize and colonize in the new environment in the compost heap.
- Growth phase, which is characterized by the rise of biologically produced temperature to mesophilic level.
- Thermophilic phase, in which the temperature rises to the highest level. This is the phase where waste stabilization and pathogen destruction are most effective. This biochemical reaction can be represented by Equations 2.1 and 2.3 for the cases of aerobic and anaerobic composting, respectively.
- Maturation phase, where the temperature decreases to mesophilic and, consequently, ambient levels. A secondary fermentation takes place which is slow and favors humification, that is, the transformation of some complex organics to humic colloids closely associated with minerals (iron, calcium, nitrogen, etc.) and finally, to humus. Nitrification reactions in which ammonia, a by-product from waste stabilization as shown in Equations 2.1 and 2.3 in the form of ammonium ion, is biologically oxidized to become nitrite (NO_2^-) and finally nitrate (NO_3^-) also occur, as follows:

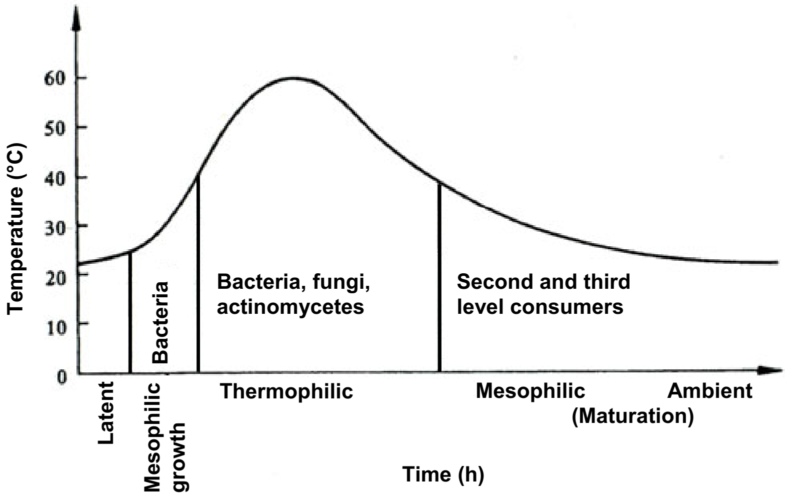

Figure 3.2 Patterns of temperature and microbial growth in compost piles

$$NH_4 + \frac{3}{2} O_2 \xrightarrow[\text{bacteria}]{\textit{Nitrosomonas}} NO_2^- + 2H^+ + H_2O \tag{3.1}$$

$$NO_2^- + \frac{1}{2} O_2 \xrightarrow[\text{bacteria}]{\textit{Nitrobactor}} NO_3^- \tag{3.2}$$

Combining Equations 3.1 and 3.2, the overall oxidation reaction for nitrification is:

$$NH_4^+ + 2O_2 \longrightarrow NO_3^- + 2H^+ + H_2O \tag{3.3}$$

Since NH_4^+ is also synthesized into cell tissue, a representative reaction for cell synthesis is:

$$NH_4^+ + 4\,CO_2 + HCO_3^- + H_2O \rightarrow C_5H_7O_2N + 5O_2 \tag{3.4}$$

The overall nitrification reaction, combining Equations 3.3 and 3.4 is:

$$22\ NH_4^- + 37O_2 + 4CO_2 + HCO_3^- \rightarrow 21NO_3^- + C_5H_7O_5N + 20H_2O + 42\ H^+ \quad (3.5)$$

The nitrifying bacteria responsible for nitrification consist of two main groups i.e. the *Nitrosomonas* which converts NH_4^+ to NO_2^- and the *Nitrobactor* which converts NO_2^- to NO_3^-. The nitrifying bacteria have a relatively slow growth rate and are inactive at temperatures greater than 40°C (Alexander 1961), hence they will become active normally after the reactions of organic waste decomposition (the growth phase and thermophilic phase) are complete. Since NO_3^- is the form of N which is readily available for crop uptake, the maturation phase thus becomes an essential step in composting to produce good-quality compost for use as fertilizer/soil conditioner.

At this stage, the organisms classified as second- and third-level consumers (Figure 3.3), such as protozoa and beetles, will grow and will feed on the first-level consumers (e.g. bacteria, fungi, actinomycetes).

The composted products after maturation can be used as fertilizers or soil conditioners to crops. In this way, the nutrients returned as compost are in the form of microbial protoplasm and/or organic compounds that break down slowly. Other nutrients present in the compost such as nitrates are readily available to crops.

In the aerobic composting systems, the degradation of organic matter depends on the presence of oxygen. Oxygen serves two functions in the metabolic reactions: as the terminal electron acceptor in aerobic respiration; and, as a substrate required for the operation of the class of enzymes called oxygenase (Finstein *et al.* 1980).

Organic matter generally degrades more rapidly and more completely if oxygen is plentiful. This can be explained by the presence of the large amount of free energy produced for microbial growth where the prominent electron acceptor is oxygen. Oxygen can be incorporated into molecules devoid of this element with the function of the widely distributed, non-substrate specific and inducible enzymes ' oxygenases'. This is often the first necessary step in the metabolic sequences leading to the degradations of molecules resistant to biological attack. Classes of organic microcontaminants acted upon by oxygenase include saturated alkanes, aromatic hydrocarbons, and halogenated hydrocarbons; while anaerobic environment lack this mechanism (Finstein *et al.* 1980). In anaerobic composting, the free energy (heat) produced is much less than that of aerobic composting and thus the longer time required for organic decomposition and pathogens inactivation.

The kinetics of composting systems is a subject of vital interest to the design engineer who must determine the type and size of composting plants and the detention time required to achieve a certain degree of organic stabilization and pathogen inactivation. Haug (1980) conceptually described the various rate-controlling phenomena occurring during aerobic composting which include:

- Release of extracellular hydrolytic enzymes by the cell and transport of the enzymes to the surface of the substrate;
- Hydrolysis of substrate molecules into lower molecular weight, soluble fractions;
- Diffusion transport of solubilized substrate molecules to the cell;
- Diffusion transport of substrate into the microbial cell, floc or mycelia;
- Bulk transport of oxygen (usually in air) through the voids between particles;
- Transport of oxygen across the gas-liquid interface and the unmixed regions which lie on either side of such an interface;
- Diffusion transport of oxygen through the liquid region;
- Diffusion transport of oxygen into the microbial cell, floc or mycelia; and
- Aerobic oxidation of the substrate by biochemical reaction within the organism.

In practice, the design of a composting plant is based on such criteria as: type and quantity of materials to be composted, time required for waste stabilization and pathogen inactivation, degree of compost maturity, type of composting process to be employed, and area and location of the composting plant. Data from laboratory and pilot-scale investigation together with knowledge of past experiences greatly help in designing an efficient composting plant.

3.3 BIOLOGICAL SUCCESSION

Composting is a biological process in which organic wastes are converted into stabilized humus by the activity of complex organisms which are naturally present in the wastes. These include microorganisms such as bacteria, fungi and protozoa and may also involve invertebrates such as nematodes, earthworms, mites, and various other organisms (Figure 3.3).

The organic wastes are firstly decomposed by the first level consumers such as bacteria, fungi (molds), and actinomycetes. Waste stabilization is accomplished mainly through the bacterial reactions. Mesophilic bacteria are the first to appear. Thereafter, as the temperature rises, thermophilic bacteria appear which inhabit all parts of the compost heap. Thermophilic fungi usually grow after 5-10 days of composting. If the temperature becomes too high, i.e., greater than 65-70°C, the fungi, actinomycetes and most bacteria are inactive, and only spore-forming bacteria can develop. In the final stages, as the temperature declines, members of the actinomycetes become the dominant group which may give the heap surface a white or grey appearance.

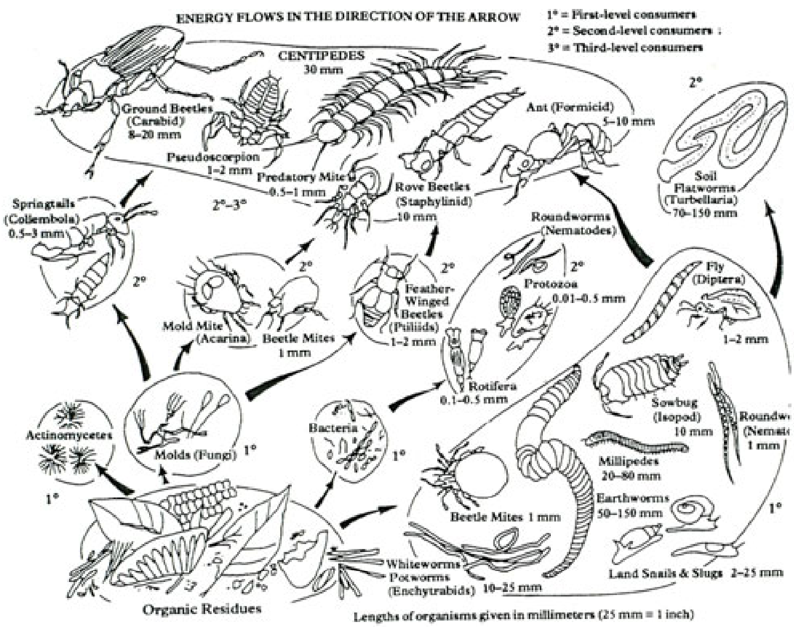

Figure 3.3 Food web of the compost pile (Dindal 1978; reproduced by permission of the JG Press)

Thermophilic bacteria mostly *Bacillus* spp. (Strom 1985), play a major role in the decomposition of proteins and other carbohydrate compounds. In spite of being confined primarily to the outer layers of the compost piles and becoming active only during the latter part of the composting period, fungi and actinomycetes play an important role in decomposing cellulose, lignins and other more resistant materials, which are attacked after the readily decomposed materials have been utilized. The common species of actinomycetes are reported to be *Streptomyces* and *Thermoactinomyces*, while *Aspergillus* is the common fungus species (Strom 1985).

After these stages, the first level consumers become the food for second level consumers such as mites, beetles, nematodes, protozoa and rotifers. Third level consumers such as centipedes, rove beetles and ants prey on the second level consumers. A schematic diagram showing the growth patterns of different level consumers with composting time and temperature is presented in Figure 3.2.

In order for the composting process to function effectively, a suitable number of organisms must be present which are capable of attacking the types of wastes to be stabilized. These organisms are naturally present in the wastes, such as nightsoil, animal manure, and wastewater sludges; hence, compost seeding is usually not necessary. Although packages of compost inoculum are commercially available, controlled scientific tests showed no increased benefits over natural sources of organisms (Dindal 1978). However, some types of agricultural wastes such as rice straw, leaves, and aquatic weeds which do not readily have these organisms may require the seeding of nightsoil or sludge at the starting period.

3.4 ENVIRONMENTAL REQUIREMENTS

The effectiveness of a composting process is dependent upon the groups of organisms that inhabit and stabilize the organic wastes. Any process failure may be due to some unbalanced chemical and physical conditions in the compost piles which are unfavorable for microbial growth. The major environmental parameters needed to be properly controlled in the operation of composting processes are as follows:

3.4.1 Nutrient balance

The most important nutrient parameter is the carbon/ nitrogen or C/N ratio. Phosphorus (P) is next in importance, and sulfur (S), calcium (Ca) and trace quantities of several other elements, all play a part in cell metabolism.

Alexander (1961) reported that between 20-40% of C substrate in the organic wastes (compost feed) is eventually assimilated into new microbial cells in composting, the remainder being converted to CO_2 in the energy-producing processes. However, these cells contain approximately 50% C and 5% N on a dry weight basis or the C/N ratio is about 10/1. If 30 % of C substrate is converted into microbial cells, to make a balanced substrate proportion of cell growth, the initial C/N ratio of the compost feed should be adjusted to 30/1. Accordingly, the requirement of N in the composting feed is 2 - 4% of initial C, i.e. a C/N ratio range of about 20/l - 40/1 should be considered optimum for biological processes.

The C/N ratios of various wastes are shown in Table 3.1. Except for horse manure and potato tops, the C/N ratios of other wastes should be adjusted to the optimum value of 25/1 prior to being composted. In practice, accurate calculation and adjustment of optimum C/N ratio are made difficult by the following factors (Gray *et al.* 1971).

Table 3.1 C/N ratio of various wastes

Materials	**Nitrogen (percent of dry weight)**	**C/N ratio**
Nightsoil	5.5 - 6.5	6 to 10
Urine	15 - 18	0.8
Blood	10 to 14	3
Animal tankage	-	3
Cow manure	1.7	18
Poultry manure	6.3	15
Sheep manure	3.8	-
Pig manure	3.8	-
Horse manure	2.3	25
Raw sewage sludge	4 to 7	11
Digested sewage sludge	2 to 4	
Activated sludge	5	6
Grass clippings	3 to 6	12 to 15
Nonlegume vegetable waste	2.5 to 4	11 to 12
Mixed grasses	2.4	19
Potato tops	1.5	25
Straw, wheat	0.3 to 0.5	128 to 150
Straw, oats	1.1	48
Saw dust	0.1	200 to 500

From Golueke (1972); reproduced by permission of the JG Press

- Some of the C substrate such as cellulose and lignin are highly resistant to biological break-down, and are only decomposed over a long period of time.
- Some of the nutrients such as keratin-type proteins are in the accessibly difficult form and is not easily available during much of the composing process.
- Some nitrogen fixation can take place through the bacteria *Azotobacter* sp. especially in the presence of adequate phosphatic material.
- Analysis of C concentration may be difficult and the following relationship providing an accuracy of within 2-10% is proposed (Gotaas 1956):

$$\% \text{ C} = \frac{100 - \% \text{ ash}}{1.8} \tag{3.6}$$

Percent ash in Equation 3.6 refers to materials remaining after being burnt at 550°C for 1 hour. For some types of wastes that contain a large portion of plastics (which do disappear at 550°C), the use of Equation 3.6 will give a high value of % C which is largely non-biodegradable.

Based on the above reasons, the initial C/N ratios of between 20/1 to 40/1 should serve adequately as an optimum range for composting.

If the initial C/N ratio of materials to be composted is greater than the optimum value (such as sawdust and wheat straw), the microorganisms will have growth limitations due to the lack of N. They will have to go through many life cycles, oxidizing the excessive C until a final C/N ratio of about 10/1 is reached in the composted products. Therefore, an extra composting time is needed and a smaller quantity of final humus is obtained. The relationship between aerobic composting time and C/N ratio observed during studies at the University of california, USA, is as follows (reported in Haug 1980):

Initial C/N ratio = 20/1,
    Composting time about 12 days
Initial C/N ratio = 20/1-50/1,
    Composting time about 14 days
Initial C/N ratio = 78/1,
    Composting time about 21 days

With lower than optimum initial C/N ratio (such as the cases of nightsoil and sludge), N will probably be lost as NH_3 gas, especially under conditions of high temperatures and pH and forced aeration, hence a loss of the valuable nutrient to atmosphere.

An example showing a method of calculation of appropriate mixing ratio of some raw materials to be composted is given below.

Example 3.1

Sludge from a septic tank has the following characteristics:

C/N ratio	= 15/l (dry weight basis)
Total solids	= 10%
Volatile solids	= 90% of total solids
Specific gravity	= 1.1

Determine the quantity of rice straw needed to be mixed with this septic tank sludge to raise the C/N ratio of the mixture to 30/l, suitable for composting. Rice straw has a C/N ratio of 80/l, moisture content 50%, bulk density = 100 kg/m^3 and N = 0.2 % of dry weight.

For the sludge that has 90 % volatile solids, the percent ash is 10, Equation 3.6 gives:

$$\% \text{ C} = \frac{100\text{-}10}{1.8} = 50\% \text{ of total solids}$$

Let x be kg dry weight of rice straw needed to be mixed with 1 kg dry weight of septic tank sludge (or total solids)

For 1 kg dry weight of septic tank sludge, C content = 1(0.5) kg,
N content = 1(0.5) (1/15) kg.

For x kg dry weight of rice straw, N content = x (0.2/100) kg,
C content = x(0.2/100)(80/l) kg.

Therefore C/N of the mixture is,

$$\frac{1(0.5) + x\,(0.2/100)\,(80/1)}{1(0.5)\,(1/15) + x\,(0.2/100)} = \frac{30}{1}$$

$$x = 5 \text{ kg}$$

$$\text{Volume of rice straw required} = \frac{5}{0.5(100 \text{ kg}/1000\text{L})} = 100 \text{ L}$$

$$1 \text{ kg dry weight of septic tank sludge} = \frac{1}{0.1(1.1)} = 9.09 \text{ L}$$

Therefore, 9.09 L septic tank sludge requires 100 L of rice straw to be mixed to raise the C/N ratio to 30/l.

3.4.2 Particle size and structural support of compost pile

The particle size of composting materials should be as small as possible so as to allow for efficient aeration (in case of aerobic composting) and to be easily decomposed by the bacteria, fungi and actinomycetes. Therefore municipal solid wastes and agricultural residues, such as aquatic weeds and straws, should be shredded into small pieces prior to being composted. Nightsoil, sludge, and animal manure usually contain fine solid particles suitable for microbial decomposition. However, other materials such as organic amendments and/or bulking materials are needed to be added to these wastes to raise the C/N ratio, provide structural support for the compost pile, and create void spaces in case of aerobic composting. Organic amendments are materials added to the composting feed to increase the quantity of degradable organic C, reduce bulk weight, and increase air voids of the compost mixture; examples of these materials are sawdust, rice straw, peat, rice hulls, and domestic refuse. Bulking materials can be either organic or inorganic of sufficient size which, when added to sludge, will provide structural support and maintain air space in the compost mixture. Dried water hyacinth (*Eicchornia crassipes*) and rice straw, shredded into small pieces (2-3 cm long), and were found to be suitable as both organic amendments and bulking materials for the composting of nightsoil (Polprasert *et al.* 1980).

3.4.3 Moisture control

An optimum moisture content of the compost mixture is important for microbial decomposition of the organic waste. Since water is essential for nutrient solubilization and cell protoplasm, moisture content below 20% can severely inhibit the biological process. Too-high moisture content will cause leaching of nutrients and pathogens from the compost pile. In aerobic composting, too much water will block air passage, causing the compost pile to become anaerobic. A moisture content of between 50-70% (average 60%) is most suitable for composting and should be maintained during the periods of active bacterial reactions, i.e. mesophilic and thermophilic growth (Figure 3.2).

Since nightsoil, sludge, and animal manure usually have moisture contents higher than the optimum value of 60% (see Chapter 2), the addition of organic amendments and bulking materials will help reduce the moisture content to a certain degree. On the other hand, most agricultural residues have moisture contents lower than 60% and some water have to be added during the composting period of these wastes. For batch operation of composting, the moisture content of the compost mixture can be controlled by adding water to the compost piles one or two times daily. The moisture content should be controlled at the optimum range until the thermophilic period is completed which is evidenced from the decline of temperature in the compost pile and the occurrence of the second- and third-level consumers (Figure 3.3).

For a composting system which is continuously operated, the control of moisture content of compost mixture can be achieved through the recycle of composted product, as schematically shown in Figure 3.4 (Haug 1979).

Assuming organic amendments or bulking materials have been added to the compost feed already, a mass balance on total wet solids is written as:

$$X_c + X_r = X_m \tag{3.7}$$

For dry solids:

$$S_c X_c + S_r X_r = S_m X_m \tag{3.8}$$

$$S_c X_c + S_r X_r = S_m (X_c + X_r) \tag{3.9}$$

Where:

X_c = total wet weight of compost feed produced per day
X_p = total wet weight of compost product produced per day
X_r = total wet weight of compost product recycled per day
X_m = total wet weight of mixed material entering the compost per day

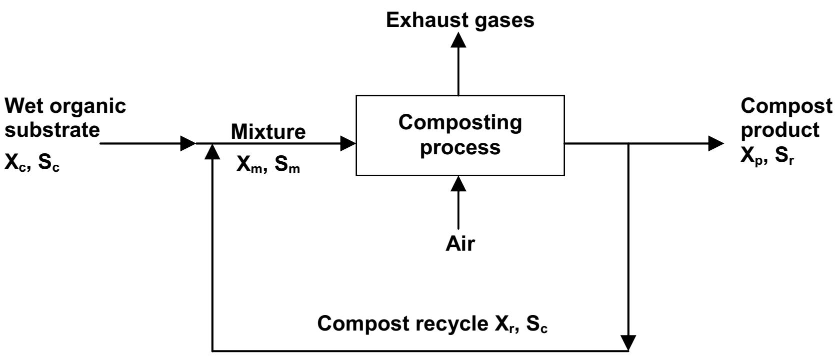

Figure 3.4 Schematic mass balance diagram for sludge composting showing inputs of compost feed and compost recycle, and compost product (adapted from Haung 1979; reproduced by permission of the Water Pollution Control Federation USA)

S_c = fractional solids content of compost feed
S_r = fractional solids content of compost product and compost recycles
S_m = fraction solids content of mixture before composting
V_c = volatile solids content of compost feed, fraction of dry solids

V_r = volatile solids content of compost product and recycle fraction of dry solids
V_m = volatile solids content of mixture, fraction of dry solids
R_w = recycle ratio, based on total wet weight of compost product recycled to total wet weight of compost feed
R_d = recycle ratio, based on dry weight of compost product recycled to dry weight of compost feed

$$R_W = \frac{X_r}{X_c} \tag{3.10}$$

Substituting Equation 3.10 into Equation 3.9 and rearranging:

$$R_w = \frac{S_m - S_c}{S_r - S_m} \tag{3.11}$$

Similarly

$$R_d = \frac{S_r\, X_r}{S_c\, X_c} \tag{3.12}$$

Substituting Equation 3.12 into Equation 3.9 and rearranging:

$$R_d = \frac{(S_m/S_c)-1}{1-(S_m/S_r)} \tag{3.13}$$

Equations 3.11 and 3.13 can be used to calculate the compost recycle ratios based on wet weight and dry weight, respectively. For the desired moisture content of 60% in the compost pile ($S_m = 0.4$), these 2 equations are graphically interpreted in Figures 3.5 and 3.6, respectively.

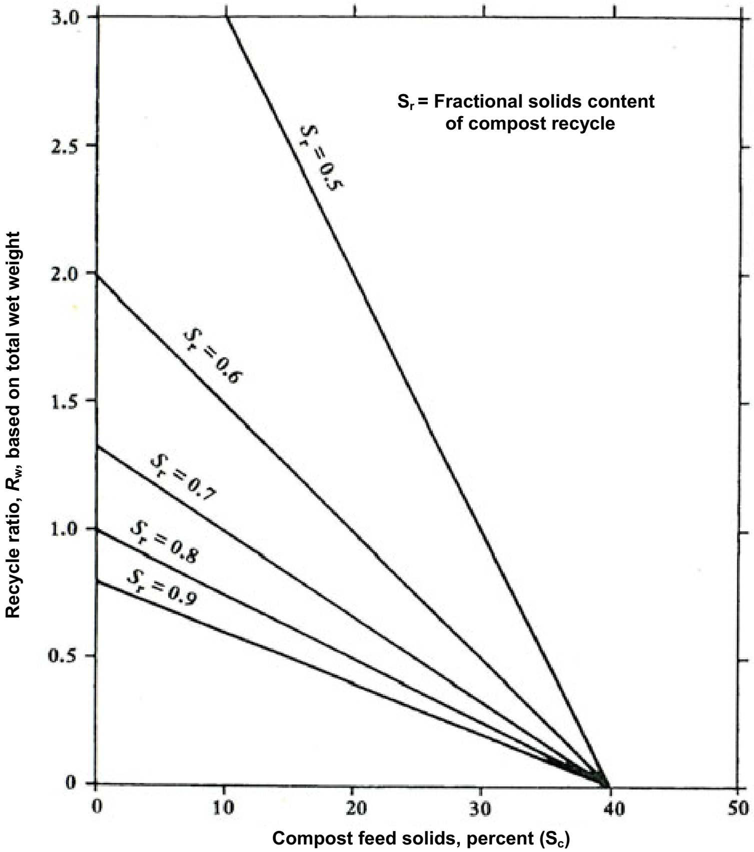

Figure 3.5 Effect of compost feed solids content on the wet weight recycle ratio needed to achieve a 40% mixture solids content (Haug 1979; reproduced by permission of the Water Pollution Control Federation USA)

Example 3.2

From the data of Example 3.1, suppose the moisture content of the composted product is 20%. Determine the quantity of the composted product needed to be recycled to achieve 40% mixture solids content.

From Example 3.1, moisture content of the mixture between septic tank sludge and rice straw is:

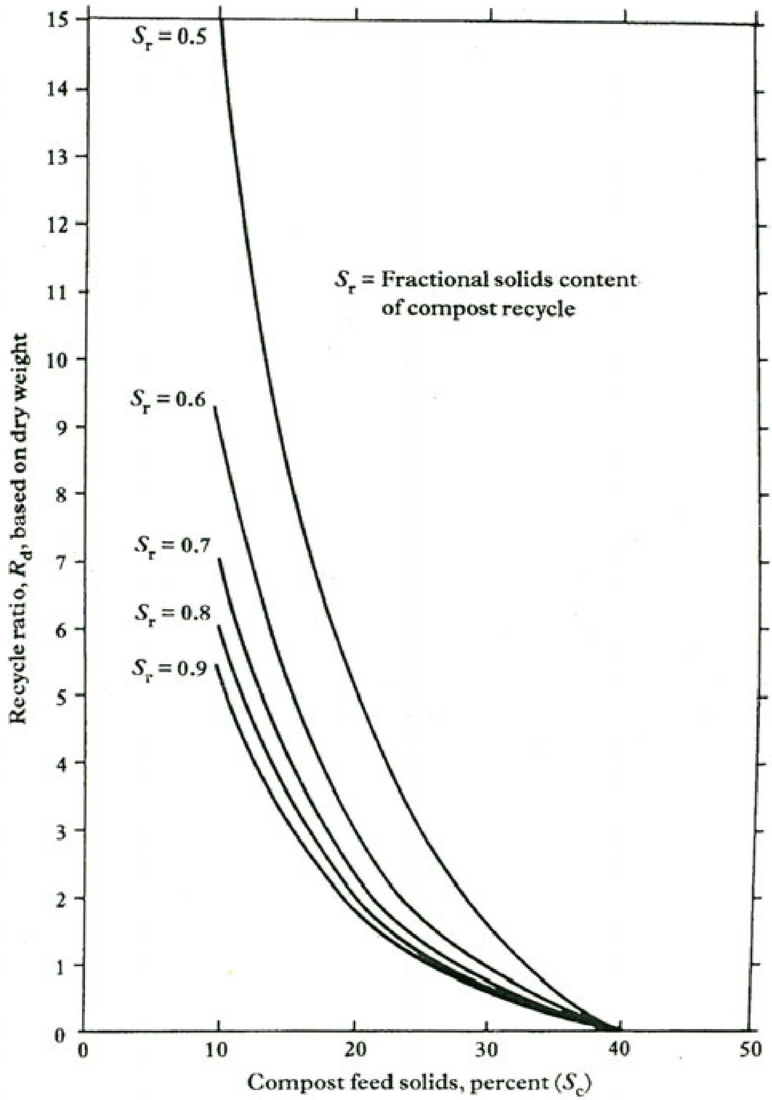

Figure 3.6 Effect of compost feed solids content on the dry-weight recycle ratio needed to achieve a 40 percent mixture solids content (Haug 1979; reproduced by permission of the Water Pollution Control Federation USA)

$$\frac{(1/0.1)(90) + (5/0.5)\,(50)}{(1/0.1) + (5/0.5)} = \frac{14}{20}\,(100) = 70\%$$

Or the compost feed solids are = 30%.

From Equation 3.13,

$$R_d = \frac{(S_m/S_c\text{-}1)}{(1\text{-}S_m/S_r)} = \frac{(0.4/0.3) - 1}{1 - (0.4/0.8)} = 0.67$$

From Equation 3.11,

$$R_w = \frac{S_m - S_c}{S_r - S_m} = \frac{0.4 - 0.3}{0.8\text{-}0.4} = 0.25$$

Also from Figure 3.6, at S_r = 0.8 and the compost feed solids of 30%, the value of R_d = 0.7; and from Figure 3.5, R_w = 0.25.

Therefore, for composting 6 kg dry weight of the mixture of septic tank sludge and rice straw, the quantity of compost recycle is

6 x 0.67 = 4 kg dry weight or 20 x 0.25 = 5 kg wet weight, in order to achieve a 40% solids content of the compost mixture.

3.4.4 Aeration requirements

Aerobic composting needs proper aeration to provide sufficient oxygen for the aerobic microbes to stabilize the organic wastes. This is accomplished through some non-mechanical means such as periodic turning of the compost piles, insertion of perforated bamboo poles into the compost piles, or dropping of compost heaps from floor to floor. A more effective, mechanical way is the forced-air aeration in which air is pumped through perforated pipes and orifices into the compost heaps.

Because non-mechanical aeration cannot supply sufficient oxygen to the microorganisms, aerobic conditions prevail only at the outer surface of the compost heaps, while facultative or anaerobic conditions exist inside. The composting rate is accordingly slow and requiring a longer composting period.

When mechanical aeration is to be employed, the quantity or rate of air flow has to be properly controlled. Too much aeration is wasteful and can cause a loss of heat from the compost piles, while too little aeration would lead to the occurrence of anaerobic conditions inside the compost piles.

A simple method to determine aeration requirements is based on the stoichiometric reaction of waste oxidation. A knowledge of the chemical compositions of the wastes to be composted or oxidized (Table 3.2) is useful for the calculation. Since compost feed is a combination of various organic compounds, for practical purposes, the formulae $C_{10}H_{19}O_3N$ and $C_5H_7O_2N$ have been used to represent its chemical composition. The stoichiometric equations for complete oxidation of these compounds are as follows:

$$C_{10}H_{19}O_3N + 12.5\ O_2 \rightarrow 10\ CO_2 + 8\ H_2O + NH_3 \tag{3.14}$$

$$C_5H_7O_2N + 5O_2 \rightarrow 5\ CO_2 + 2\ H_2O + NH_3 \tag{3.15}$$

Table 3.2 General chemical composition of various organic materials (Haug 1980)

Waste component	Typical chemical composition
Carbohydrates	$(C_6H_{10}O_5)_x$
Protein	$C_{16}H_{24}O_5N_4$
Fat and oil	$C_{50}H_{90}O_6$
Sludge	
Primary	$C_{22}H_{39}O_{10}N$
Combined	$C_{10}H_{19}O_3N$
Refuse (total organic fraction)	$C_{64}H_{104}O_{37}N$
	$C_{99}H_{148}O_{59}N$
Wood	$C_{295}H_{420}O_{186}N$
Grass	$C_{23}H_{38}O_{17}N$
Garbage	$C_{16}H_{27}O_8N$
Bacteria	$C_5H_7O_2N$
Fungi	$C_{10}H_{17}O_6N$

Parts of NH_3 generated from the above reactions will be lost through volatilization if pH of the compost piles is above 7. The remaining NH_3 will be nitrified to become NO_3^- during the maturation or curing of the composted products. Example 3.3 shows a method to determine aeration requirements based on the stoichiometric equations.

Example 3.3

Suppose Equation 3.14 represents the reaction occurring during aerobic composting of septic tank sludge. Calculate the amount of air required to completely oxidize this sludge.

$$\underset{(201)}{C_{10}H_{19}O_3N} + \underset{(400)}{12.5O_2} \rightarrow 10CO_2 + 8H_2O + NH_3 \tag{3.14}$$

$$1\text{g of } C_{10}H_{19}O_3N \text{ requires } O_2 = 2\text{ g}$$

Assume septic tank sludge contains 75% volatile solids of which 50% is biodegradable (as represented by $C_{10}H_{19}O_3N$):

Therefore, the amount of O_2 required per 1 g of septic tank sludge is 2(0.75)(0.5) = 0.75 g.

Since air contains 23% O_2 (by weight), the amount of air required is 0.75/0.23 = 3.26 g.

The specific weight of air is 1.20 g/L at 25 °C and 1 atmospheric pressure.

The volume of air required to oxidize 1 g (dry weight) of septic tank sludge is 3.26/1.20 = 2.72 L.

Note: This is a theoretical method of calculating aeration requirement. In practice, the amount of air supply should be adjusted according to the biological reactions taking place, e.g. thermophilic reactions will require oxygen several times higher than those of mesophilic and maturation reactions (see Figure 3.2). Additional amount of air needs to be supplied to compensate for loss to atmosphere, which can be up to 95-99 percent.

3.4.5 Temperature and pH

The biologically produced heat generated within a composting mass is important for two main reasons:

- To maximize decomposition rate; and
- To produce a material which is microbiologically ‘safe’ for use

It is generally known that compost temperatures greater than 60-65 °C, above thermophilic range, will significantly reduce the rate of biodegradation in compost piles. A recent work using compost samples from a full scale composting plant showed the optimal temperature for composting, as measured by microbial activity (incorporation of [^{14}C] acetate) was consistently below 55°C (McKinley *et al.* 1985). On the other hand, most pathogenic microorganisms are inactivated effectively at temperatures above 50°C (Figure 3.1). So the key concern is to control temperatures in the compost piles in such a way as to optimize both the breakdown of organic material and pathogen inactivation (approximately 55°C). Temperature can be controlled by the adjustment of aeration and moisture content and the utilization of screened compost as insulation cover of the compost piles.

Temperature patterns in compost piles influence the types and species of microorganisms' growth. Mesophilic temperature (25-45°C) is developed first in composting, followed by thermophilic temperature (50-65°C). After this phase, most organic substrates will have been stabilized, resulting in the decline of temperature to mesophilic and eventually to ambient level (Figure 3.2). In many cases, the thermophilic temperature can even reach 55-65°C and last for a few days, causing an effective inactivation of the pathogens.

Aerobic composting normally proceeds at a neutral pH and rarely encounters extreme pH drop or rise. A slight pH drop may occur during the first few days of anaerobic composting due to the production of volatile fatty acids. After this period, the pH becomes neutral again when these acids have been converted to methane and carbon dioxide by the reactions of methane-forming bacteria.

3.5 COMPOSTING MATURITY

There are many criteria to judge the maturity or completion of a composting process. In general, a composted product should contain a low organic content that will not undergo further fermentation when discharged on land, and the pathogens inactivated. Some of the approaches to measure the degree of compost stabilization are (Haug 1980):

- Temperature decline at the end of batch composting
- Decrease in organic content of the compost as measured by the volatile solid (VS) content, chemical oxygen demand (COD), percent carbon content, and C/N ratio
- Presence of particular constituents such as nitrate, and the absence of others such as ammonia
- Lack of attraction of insects or development of insect larvae in the final product
- Absence of obnoxious odour

- Presence of white or grey colour due to the growth of actinomycetes.

In cases where the composted products are to be applied to crops and public health aspects are of concern, the time required for pathogen die-offs during composting is another important criterion to be considered (see Figure 3.1). More information about pathogen die-off during composting and the public health risks are discussed in section 3.7.

Because compost materials usually contain some biologically resistant compounds, a complete stabilization during composting may not be achieved. The time required for a satisfactory degree of composting would depend on the environmental factors in and around the compost heap as were described in section 3.4. Under suitable conditions, aerobic composting normally takes about 10-30 days, while anaerobic composting can last from 45 to 100 days. The maturing or curing time of compost may be approximately the same as those required for organic stabilization. Some manufacturers have produced mechanical composting reactors which claim to yield satisfactory compost within a short period, e.g. 24 hours. However, these reactors are both expensive and difficult to operate, and the composted materials will usually need an additional time for curing or nitrification.

It should be noted that in batch composting, the temperature pattern and biological succession developed in the compost piles are similar to those shown in Figures 3.2 and 3.3, respectively. Because both the stages of waste stabilization and consequently curing occur during batch composting, the composted product is suitable to be used in agriculture or horticulture.

The continuous composting process is normally aerobic and has a semi-continuous plug-flow passage of composting materials through a reactor structure, and temperatures of the reactor contents are continuously in the thermophilic range. Depending on the specific design, the material is translocated through the structure as part of the tumbling action in a large revolving drum, by the action of augers force through the mass, or by gravity. These approaches may provide the gas exchange by forcing air through the mass. Residence time in the reactor is 1-10 days with 5 days being typical. The material displaced from the continuous stage is biologically stabilized (i.e. the reaction of Equation 2.1 is achieved, but mostly not nitrified (i.e. reaction of Equation 3.5 is not achieved). It should be processed further in the curing stage to allow for nitrification to occur and to make the composted products suitable for agricultural reuse. Composting may be employed for the purpose of sludge dewatering or drying. In this case, there is no need for the nitrification reactions to take place and the composted products from continuous reactors can be disposed off in sanitary landfills or reused in non- agricultural activities.

An experienced compost operator can, most of the time, recognize the maturity of a composted product. However, it is advisable that the quality of the composted products be regularly checked for the nutrient contents and presence of any pathogenic microorganisms. Chemical fertilizers can be added to a composted product to make it suitable for applying to a particular crop, according to its nutrient requirement (see Table 8.7).

Details about the composting systems of both batch and continuous operation are given in section 3.6.

3.6 COMPOSTING SYSTEMS AND DESIGN CRITERIA

In this section the composting systems will be described as the on-site and off-site processes. On-site systems are the ones that compost organic wastes at the places of generation, e.g., at home or in the toilets; the composting process is usually not controlled and occur naturally. Off-site systems involve the collection and transportation of organic wastes to be composted at central treatment plants; the composting process is usually controlled either manually or mechanically. Nowadays, there are many manufacturers producing various composting units for the treatment of nightsoil, sludge, or municipal refuse; some of these units will be described herein.

3.6.1 On-site composting

Aerobic composting toilets

These types of composting toilets, often referred to as the 'multrum', were originally invented by Lindstrom and put into commercial production about 20 years ago (Rybczynski *et al.* 1978). The multrum (Figure 3.7) consists of a water-tight container with a sloping bottom. Human excreta (without flushing water) is introduced at the upper end of the container, and mixed with organic kitchen and garden wastes, introduced lower down, to increase the C/N ratio. Air ducts and a vent pipe are provided to promote aeration. The composted material moves toward the lower end and from where it is periodically removed. The decomposition period is long, up to 4 years, and the container is quite large (3 x 1 x 1 m: length x width x height). The air ducts also help to evaporate the humidity and eliminate odors, while the sloping bottom permits continuous use of a single container by separating the fresh and the decomposed materials. Another modification of the multrum is the biopit composting toilet (Figure 3.8) which incorporates a gravel soakage pit to treat and dispose of the liquid waste present in the excreta.

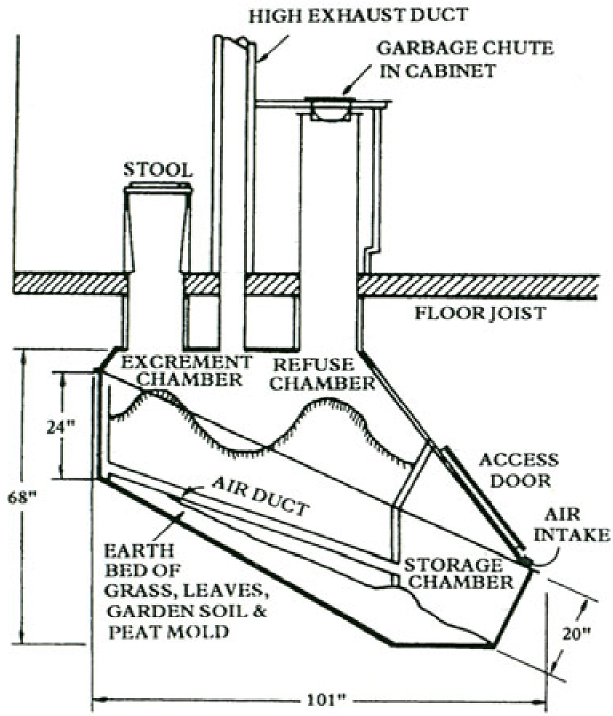

Figure 3.7 The Clivus Multrum (Rybczyski *et al.* 1978; reproduced by permission of the International Development Research Centre, Canada)

Anaerobic composting

Pit latrines (or holes in the ground) are the simplest form of anaerobic composting toilets. The excreta deposited into the pit is decomposed anaerobically. When the pit is about two-thirds full, it is filled up with dirt and left there for approximately 2-3 years. After this period, the excreta would be well stabilized and the pathogens inactivated, rendering it for satisfactory use as soil conditioner. To avoid the occurrence of obnoxious odor, ventilated improved pit (VIP) latrines were developed (Figure 3.9) which have yielded encouraging results in many places such as Zimbabwe (Morgan and Mara 1982) and Botswana (Nostrand and Wilson 1983).

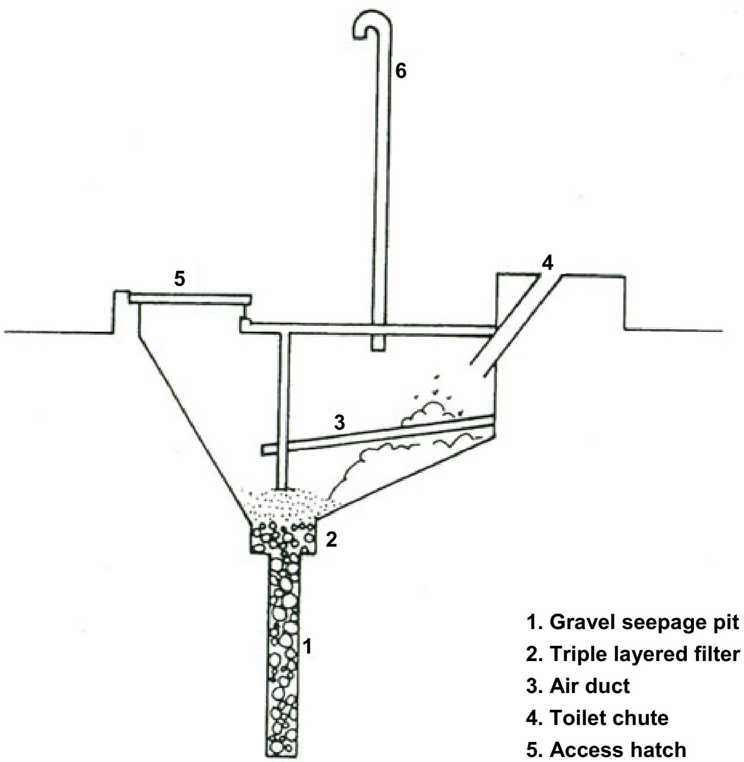

Figure 3.8 The Biopit composting toilet (Rybczynski *et al.* 1978; reproduced by permission of the International Development Research Centre, Canada)

Another version of anaerobic composting is the Vietnamese toilet (Figure 3.10) which was claimed to be the key component of a rural sanitation program for disease prevention and increased food production. It has two watertight tanks serving by turns as receptacles for defecation and composting. A hole is made on the face of each for feces deposition. Kitchen ash is added after each use to reduce odor and increase the C/N ratios. Urine is channelled in a groove into a separate vessel; this method reduces moisture content but does not decrease C/N ratio of feces in the toilet, which is favourable for the composting reactions. Apertures are made in the back wall for the collection of the composted products. The toilets are constructed above ground so as not to be submerged by rainwater.

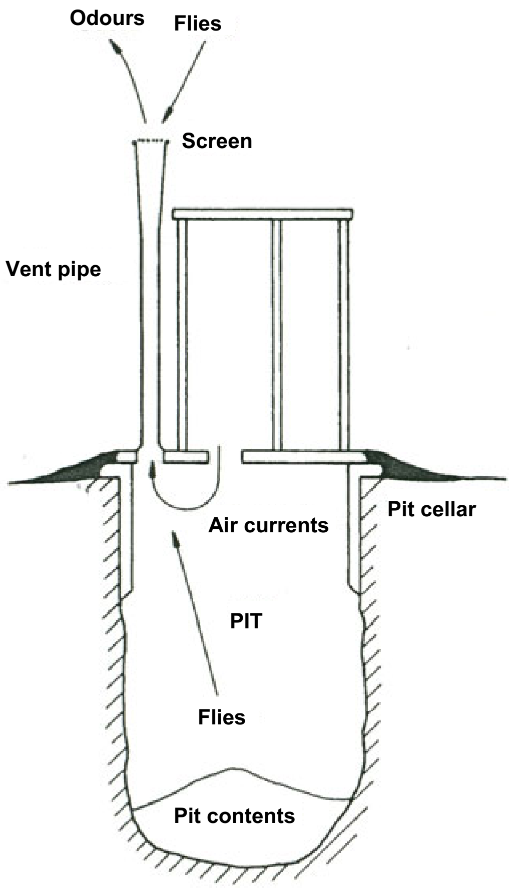

Figure 3.9 Schematic diagram of a ventilated improved pit latrine (Morgan and Mara 1982; reproduced by permission of the World Bank)

When the tank is about two-thirds full, it is filled to the brim with dried powdered earth and kept under anaerobic conditions for a few-year period. During this time, another tank is used for defecation, and the cycle is repeated. The anaerobically composted products were reported to be rich in nutrients and hygienically safe for reuse as fertilizers (McMichael 1976).

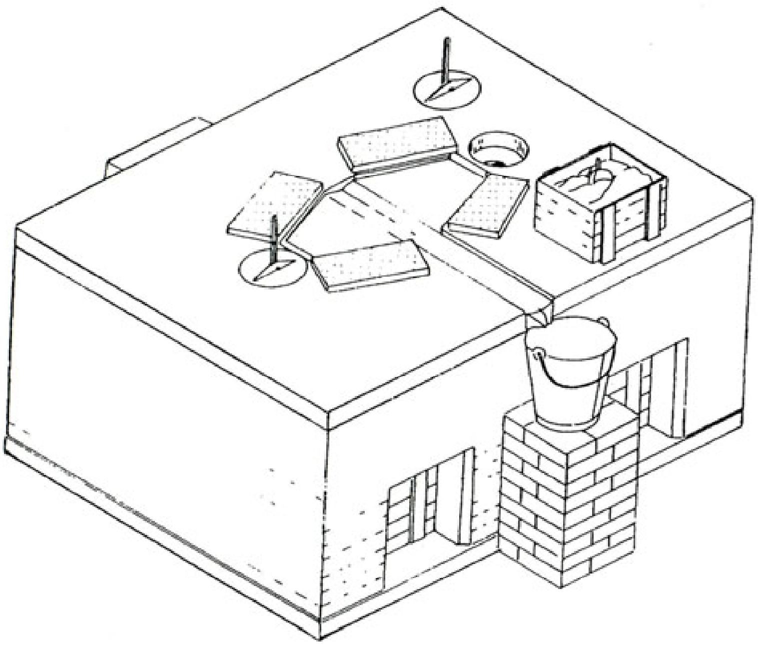

Figure 3.10 The Vietnamese composting toilet (Rybczynski *et al.* 1978; reproduced by permission of the International Development Research Centre, Canada)

3.6.2 Off-site composting

Because of large quantities of organic wastes to be decomposed, off-site composting should employ aerobic reactions to shorten the composting period and reduce the size of composting plants. Some of the aerobic composting systems currently in operation are:

Chinese ground-surface aerobic composting pile

As shown in Figure 3.11, the compost feed (a mixture of human or animal manure and vegetable matters) is piled up into a heap of approximately 2 x 2 x 0.5 m (length x width x height). The compost heap is inserted with perforated bamboo poles to facilitate natural aeration and provide a kind of structural support, and no turning of the compost pile is required. To control excessive heat loss, the compost pile is covered with rice straw or a plaster of mud (Figure 3.12). The poles can be removed after 1 or 2 days when the mud has hardened or the compost pile is structurally stable, but they can remain there for a longer period. An experiment conducted at the Asian Institute of Technology (AIT), Bangkok, Thailand, found the time required for compost stabilization to be about 60 days (Polprasert *et al.* 1980), and the composted product was suitable for use as soil conditioner. In China, more than 90% kill of *Ascaris* ova in the compost was achieved (McGarry and Stainforth 1978).

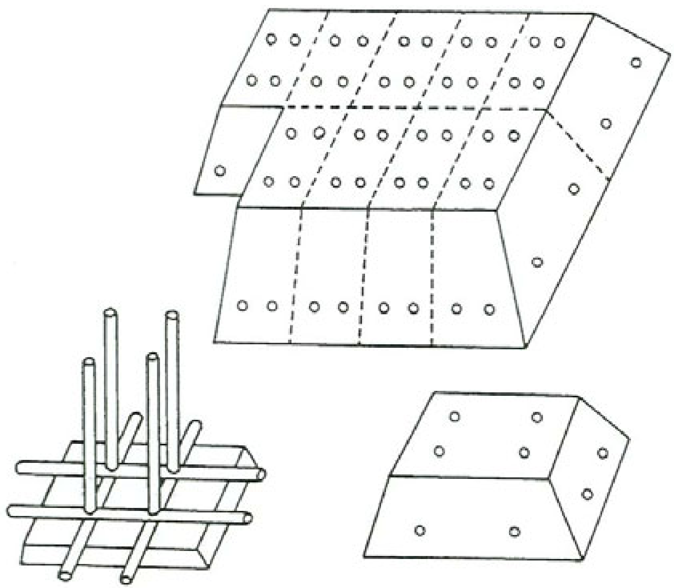

Figure 3.11 Chinese composting pile (McGarry and Stainforth 1978; reproduced by permission of the International Development Research Centre, Canada)

Windrow composting

This system involves periodic turning of the compost piles, manually about once a week, or mechanically once (or more) daily. The purpose of pile turning is to provide aeration and mix the compost materials, hence, a faster decomposition rate than that of the Chinese ground-surface aerobic composting. The approximate size of each pile is 15 x 3 x 1.5 m (length x width x height), but other sizes, subject to convenience, have been employed. The period required for compost stabilization varies according to the frequency of pile turning, being 20 - 40 days, and temperatures over 65°C in the center of the compost pile can be reached.

Figure 3.12 Chinese composting pile covered with rice straw

Forced-air aeration composting

A more efficient composting method which ensures temperatures in the upper thermophilic range and provides an effective inactivation of pathogen is called the Beltsville aerated rapid composting (BARC) method. Developed by Epstein *et al.* (1976), this method involves placing a mixture of sludge and wood chips over a base (consisted of compost and chips) and aeration piping system (Figure 3.13). The approximate size of each pile is 12 x 6 x 2.5 m (length x width x height) and is connected to a centrifugal blower to draw air through the pile (sucking) or to blow air into the pile (blowing) according to the pre-determined aeration requirements (section 3.4.4). The gases drawn into the pipe are deodorized by passing them into a pile of screened compost (Figure 3.14). The entire pile is covered with a 30 cm layer of the screened compost to minimize odors and to maintain high temperatures in the compost pile.

As shown in Figure 3.15, a rapid temperature rise to within 60-80 °C was achieved in 3-5 days of composting, and these temperatures continued for about 10 days. The distribution of temperature in a compost pile for both blowing and sucking types is shown in Figure 3.16 (Stentiford *et al.* 1985). There appeared to be uneven temperature distribution in the compost pile, with higher temperature developed at the inner part and lesser temperature at the outer portion. This uneven temperature distribution is a typical drawback of the static, non-pile-turning composting method in which pathogens present at the outer portion of the compost pile may not be effectively inactivated by the biologically produced heat.

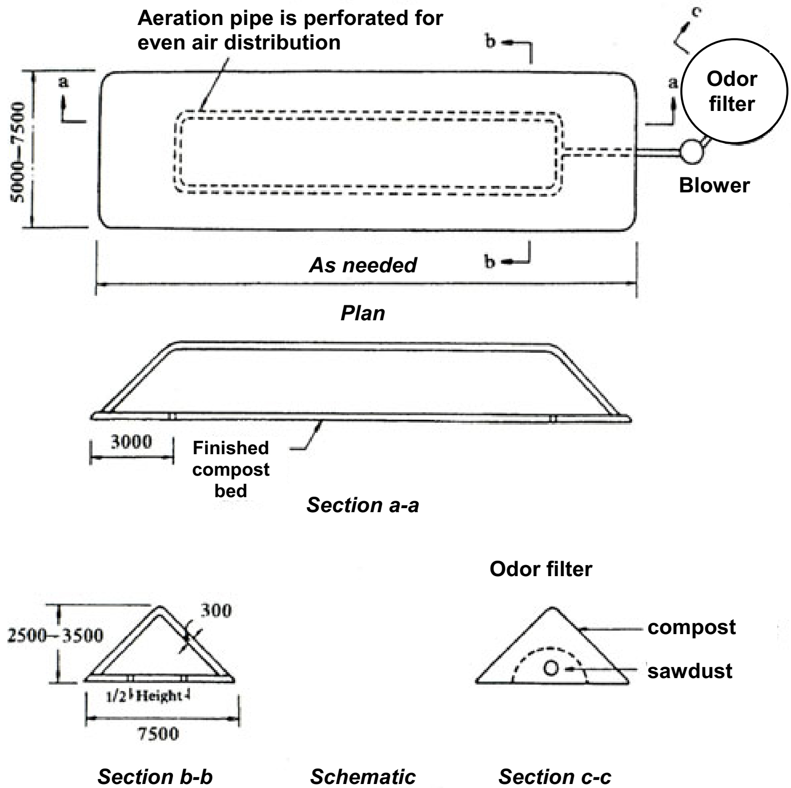

Figure 3.13 Schematic diagram of an aerated pile indicating location of aeration pipe. Loop is perforated for air distribution system (units in millimetres) (Shuval *et al.* 1981; reproduced by permission of the World Bank)

However, satisfactory reductions of indicator bacteria and viruses have been reported for the BARC system, and the system is essentially unaffected by low ambient temperatures and/or rainfall. It does not require pile turning (which is rather labor intensive), and should be applicable for nightsoil composting in hot climates (Shuval *et al.* 1981).

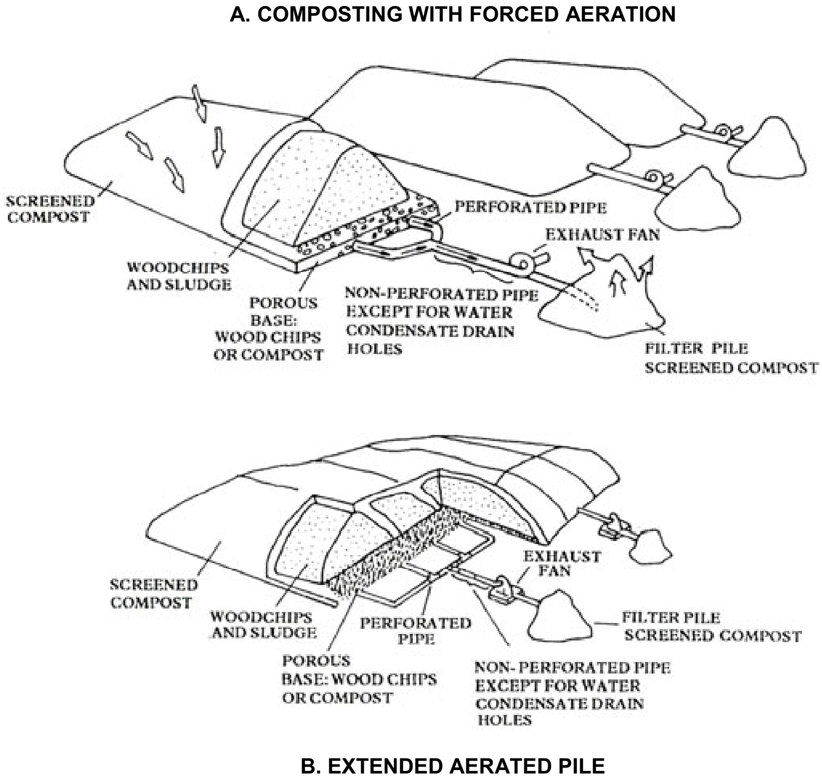

Figure 3.14 Configuration of aerated piles showing construction of pile and the arrangement of aeration pipe - the BARC system (Shuval *et al.* 1981; reproduced by permission of the World Bank)

The area required for the BARC system and conventional windrow system has been estimated to be 1 hectare (ha) per 10-12 dry tons per day of sewage sludge. This area estimate includes: (1) area for mixing the sludge or nightsoil with bulking materials, (2) area required for composting, (3) area required for storage and curing piles and long-term storage before marketing, (4) area required for screening of the final compost and separation and recycling of wood chips, (5) area required for lagooning or waste stabilization ponds to treat leachate and drainage from the composting area, and (6) area required for administration, work-shops, parking of vehicles, and storage of spare parts (Shuval *et al.* 1981).

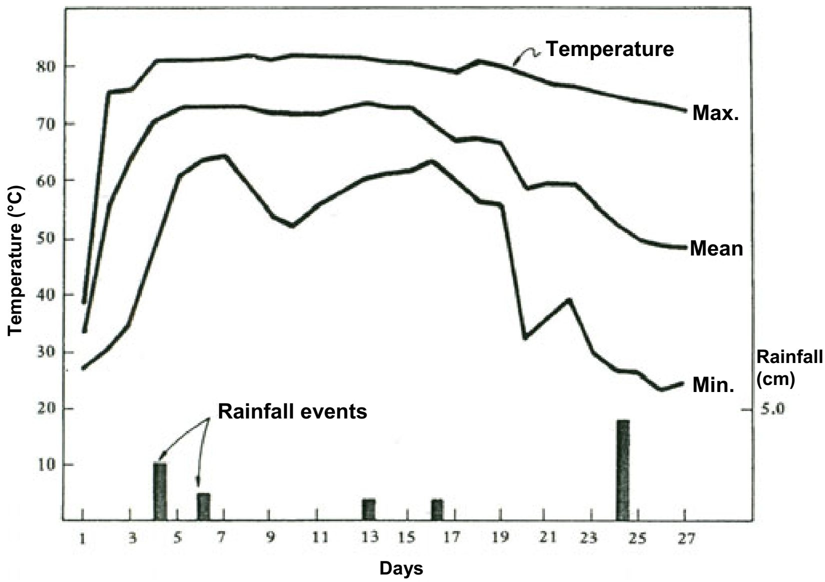

Figure 3.15 Temperature during sludge composting by the BARC system (Shuval *et al.* 1981)

Benedict *et al.* (1986) reported that with the operation capacity of 450 wet tons/day of sludge, the area required for conventional windrow composting of the Los Angeles, USA, and facility was about 20 ha. However, this total area included those used for storages of bulking agents, finished compost and equipment, and for research area; so the operating area for composting was about 15 ha or 0.03 ha for composting of 1 ton/day of wet sludge.

The DANO System

A schematic diagram of a typical DANO plant manufactured for solid waste composting is shown in Figure 3.17. It includes storage hoppers, rotary screens and magnetic separators to separate out non-compostable materials. Materials to be composted are fed into the "DANO bio-stabilizer", a cylindrical chamber, tilted slightly from the horizontal, usually about 3 - 4 m in diameter and varying from 25 to 30 m in length according to the quantity of the feeding materials. The cylinder rotates at up to 1 revolution per minute (rpm) and air is supplied by fans at a low pressure, through longitudinal ducts, each having several injector nozzles. The above conditions enhance effective aerobic decomposition of the organic matters in the cylinder in which temperatures of 60°C and over are developed inside. The steam and waste gases are exhausted through extractor fans. The composting period required for this type of compost reactor ranges from 2.5 to 5 days.

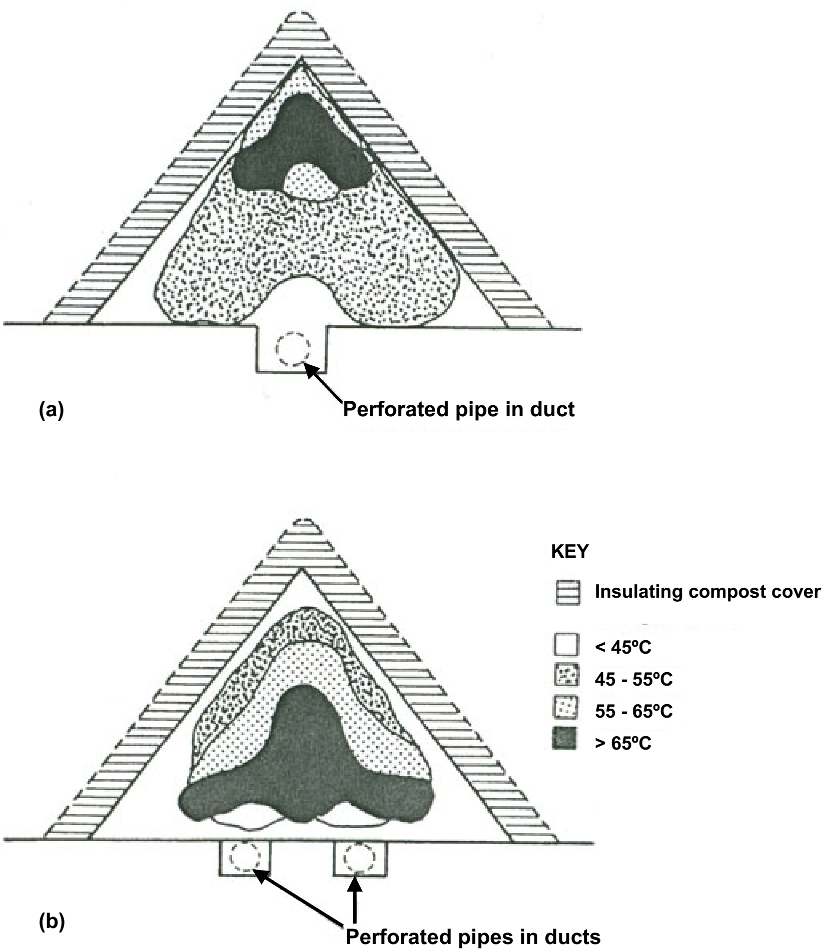

Figure 3.16 Typical temperature cross-section distributions in a pile with (a) positive pressure (blowing) aeration; and (b) negative pressure (sucking) aeration (from Stentiford *et al.* 1985; by permission of the Institute of Water Pollution Control, U.K.)

The DANO system, developed in Denmark, is presently being employed for solid waste composting in several countries throughout the world. Although very efficient in composting, the DANO system involves high capital and operation costs, and requiring skillful manpower to maintain the system. Figure

3.18 is a DANO composting plant treating part of Bangkok city, Thailand, solid wastes, while a smaller unit made for composting solid wastes generated from a community of 1,000 people in central Thailand is shown in Figure 3.19.

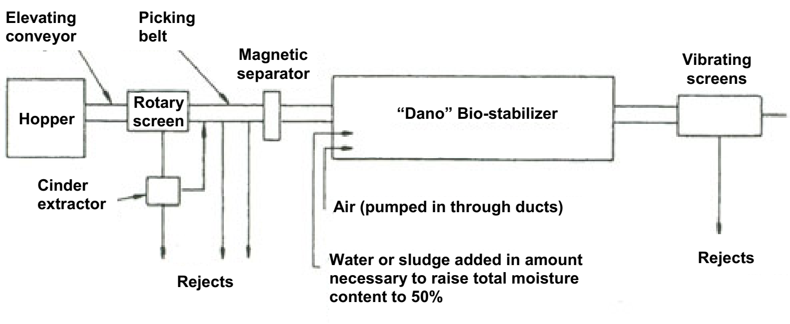

Figure 3.17 Typical DANO plant (after Flintoff and Millard 1969)

Figure 3.18 A DANO composting plant in Bangkok

Figure 3.19 Aerobic composting unit for a small community, Thailand

From Obeng and Wright (1987) and Haug (1980), composting systems can be classified into non-reactor and reactor (Tables 3.3 and 3.4, respectively). Based on the information given in Table 3.3, it appears that for the non-reactor composting systems (with proper C/N ratio and provided with some types of aeration, natural or forced-air), the time required for the first phase composting (Figure 3.2) is at least 3-4 weeks, followed by about 4 weeks of maturation or curing. The reactor composting systems (operating under aerobic conditions, Table 3.4) should require about 4 weeks. These composting systems, when properly operated according to the environmental requirements listed in section 3.4, should result in a temperature increase in the compost mixture up to 50^{o}C or more which is essential in inactivating the pathogens.

Table 3.3 Non-reactor composting systems

Composting system	Raw material	General description
Aerated static pile	Sewage sludge and wood chips	Raw sewage sludge (22% solids) is mixed with wood chips, and then transferred to a composting pad consisting of wood chips spread over perforated piping. Air is drawn through the pipe into a compost filter. The pile is maintained for 21 days followed by
	Nightsoil, paper, wood chips	The nightsoil is mixed with paper and wood chips on a concrete pad and then transferred to the composting pad, which is a bed of wood chips covering a perforated pipe. Air is drawn through the pipe into a compost filter. The pile is maintained for 21 days at
	Water hyacinth, nightsoil, rice straw	Experiment. Nightsoil, water hyacinth, and (in some cases) rice straw were mixed and composted in piles for 2-3 months. Aeration through perforated bamboo poles. Temperatures of 43-64°C were maintained for at least 8 days in the coolest parts of the
Bangalore (Indore)	Refuse, nightsoil, earth, straw, etc.	Trench in ground, 2-3 ft deep. Material placed in alternate layers of refuse, nightsoil, earth, straw, etc. No grinding. Turned by hand as often as possible. Detention time of 120-180 days. Used extensively in India
Windrow	Sewage sludge and sawdust	The sludge (30% solids) and sawdust are mixed at weight ratios 4:1. The windrows are turned for 3 months and then sold as a product "Grow Rich". The maximum temperature achieved is 74°C

Table 3.3 Non-reactor composting systems (continued)

Composting system	Raw material	General description
	Sewage sludge and wood chips	Digested sewage sludge is mixed with wood chips (1:3 volume ratio) in windrows 1.8 m high and 2.1 m wide. The windrows are turned daily for at least 2 weeks, then they are spread out, dried, and cured for 30 days. The wood chips are screened out for reuse
	Raw dewatered sewage sludge and bark	The sludge (25% solids) mixed with bark (1:3) and composted in windrows for at least 21 days. In general, temperatures of 50-75°C are maintained for at least half of this time
	Raw dewatered sewage sludge and straw	(Full-scale experimental plant) The sewage sludge (25-30% solids) was mixed with straw (1:1 volume) and composted in windrows, which were turned eight times for 3 months. At the end of this time the compost was ready for use. Temperatures of 55-60°C were
	Digested sludge and straw	Experiment. Digested sludge was mixed with straw at a ratio of 1: 1.25 in windrows for 6 weeks during which temperature of 65-70°C were achieved.

Table 3.4 Reactor composting systems

Composting system	Raw material	General description
Dano	Municipal solid wastes, sludge	Dispersed flow rotating drum, slightly inclined from the horizontal, 9-12 ft in diameter, up to 150 ft long. Drum kept about half full of reuse. Drum rotation of 0.1-1.0 rpm, 1-5 days digestion followed by windrowing. No grinding. Forced aeration into drum. Temperatures of 60°C or over are reached
Euramca (Roediger, Fermen-technik)	Dewatered sludge and recycled compost	Reactor is of the tower type with a special extraction and agitation mechanism at the bottom. The reactor is batch-operated. Once the reactor is loaded with the mixture of the sludge and agitation and assure uniform exposure to temperature. Residence time is 4-6 days.
Fairfield digester reactor	Sewage sludge and shredded paper, municipal refuse	Circular tank. Vertical screws, mounted on two rotating radial arms, keep ground material agitated. Forced aeration through tank bottom and holes in screws. Continuous flow type. Dewatered sewage sludge is mixed with shredded paper and fed into a reactor. The retention time is 5-7 days and temperature is over 60°C are reached
Forced aeration through fermenter	Dewatered sewage sludge and recycled compost	The sewage sludge and recycled compost are mixed and ground and fed into the fermenter, where the mixture is aerated and turned. The retention time is 10 days and temperatures of up to 75°C are attained. The compost is then graded and bagged
Geochemical-Eweson	Municipal refuse, sludge	Cells-in-series type. Unground refuse placed in rotating drum, 11 ft diameter, 110 ft long, slightly inclined from horizontal. Three compartments in drum. Refuse transferred to next compartment every 1-2 days for total digestion time of 3-6 days. Screened output cured in piles

Table 3.4 Reactor composting systems (continued)

Composting system	Raw material	General description
HKS	Sewage sludge and recycled compost	Reactor is of the complete-mix, rotating drum type. The sludge and recycled compost are added to a slowly rotating drum (which is stopped at night). The retention time is 24 h followed by a 2-week maturation period in a windrow. Temperatures of 60-75°C are attained
Kneer (Later version known as BAV)	Sludge, mushroom wastes, poultry wastes, organic bulking agents	Reactor consists of cylindrical tower with no interior floors or other mechanisms. Feed is introduced at the top and flows downward as product is removed by mechanical scraper from the bottom. Oxygen is supplied by forced aeration from the bottom. Residence times of 3-14 days. Temperatures of 60-85°C are achieved. Then the raw compost is matured for 6-8 weeks in a windrow
Metrowaste	Municipal refuse, animal manure, sludge	Rectangular tanks, 20 ft wide, 10 ft deep, 200-400 ft long. Refuse is ground. Residence time of about 7 days. “Agiloader” moves on rails mounted on bin walls and provides periodic agitation by turning
Naturizer (International)	Municipal refuse	Five 9-ft wide steel conveyor belts are arranged to pass material from belt to belt. Each belt is an insulated cell. Air passes upward through digester. Detention time of 6-8 days.
Open baskets	Digested sewage sludge and bark	Dewatered digested sewage sludge was mixed with bark (1:3) and composted in large baskets that could be easily stacked. Temperatures of up to 75°C were attained. The retention time in the baskets was 9-12 weeks followed by 3-4 weeks maturation in piles

Table 3.4 Reactor composting systems (continued)

Composting system	Raw material	General description
Schorr "Biocell" System	Dewatered sludge, recycled compost and ground bark	Reactor consists of a vertical tower with 10 floors one above the other. Each floor contains a hydraulically operated valve which allows material to be discharged to the next floor. Oxygen is introduced by force aeration. Dewatered sludge, recycled compost and ground bark mixed in proportions of 2: 2: 1 volume. Composting mixture is about 1 m deep on each floor. Residence time is about 3 days on each, giving a total reactor time of 30 days
T.A. Crane	Municipal refuse	Two cells consisting of three horizontal decks. Horizontal ribbon screws extending the length of each deck recirculate ground refuse from deck to deck. Air introduced in bottom of cells. Three days composting followed by curing for 7 days in a bin.
Triga	Municipal refuse, sewage sludge, bark, sawdust	Reactor is a concrete tower called a "Hygiensator" which is divided into four separate vertical compartments. Residence time of 4-15 days depending on feed and temperature of 70-80°C are achieved. Air is pulled out of top of reactor. Screw extractor removes and agitates material from bottom of reactor. Extracted material is recycled three to five times during compost period to avoid compaction at bottom. Curing period of 2-4 months.
Trough fermenter	Sewage sludge and rice hulls and recycled compost	The digested sewage sludge is mixed with rice hulls and finished compost (1:1:1 volume) and fed into a trough where it is composted for 2 weeks by forced aeration and turning. This is followed 1-2 months of maturation. Temperatures reach up to 70°C.

3.7 PUBLIC HEALTH ASPECTS OF COMPOSTING

The composting of human or animal wastes involves the following disease risks:

- From the pathogens normally present in the raw wastes (called primary pathogens), and
- From fungi and actinomycetes that grow during composting (called secondary pathogens).

The primary pathogens such as bacteria, viruses, protozoa and helminthes can initiate an infection in healthy individuals, while secondary pathogens usually infect people with debilitated immune systems, such as those weakened by primary infections or respiratory diseases (U.S. EPA 1981). Examples of primary and secondary pathogens are listed in Table 3.5; more examples of these pathogens can be found in Chapter 2.

3.7.1 Die-offs of primary pathogens

Time and temperature are the two most important parameters responsible for pathogen die-offs during composting. It should be noted that a complete inactivation of pathogens in a compost pile is rarely achieved. This is due to many reasons such as:

- The heterogeneous character of the compost materials, which may form clumps with the pathogens and protect them from being fully exposed to thermophilic temperatures.
- The uneven temperature distribution in the compost piles. Unless completely mixed continuously, the outer surfaces of a compost heap normally have a lower temperature than the inside, causing a lower efficiency of pathogen kill (see Figure 3.16).
- Partial inactivation of pathogens. Many pathogens such as spore-forming bacteria, cysts and helminthes ova are only partially inactivated during composting. They can re-grow and become infective again if exposed to a favorable environment such as under moistened conditions in crop fields.

A number of researchers (Kawata *et al.* 1977; and Cooper and Golueke 1979) reported several orders of magnitude reduction of bacteria (total coliforms, fecal coliforms and fecal streptococci) and viruses (poliovirus and coliphages) during composting. Better inactivation rates were observed with the BARC system in which these bacteria including *Salmonella* were non-detectable after 10 days of composting (Figure 3.20) and for F_2 bacteriophages about 15-20 days (Figure 3.21). The thermal death points of some common pathogens and parasites are shown in Table 3.6, while the relationships between time and temperature that cause pathogen inactivation as shown in Figure 3.1 are useful information to determine the required composting period.

The microbiological quality guidelines shown in Table 2.27 and 2.28 should be strictly observed when the composted products are to be used as fertilizers in agricultural or aquacultural activities, respectively.

Table 3.5 Examples of pathogens found in, or generated during, composting of sewage slidge, together with human diseases associated with these pathogens (U.S. EPA 1981)

Group	Example	Disease
Primary pathogens		
Bacteria	*Salmonella enteritidis*	Salmonellosis (food poisoning)
Protozoa	*Entamoeba histolytica*	Amoebic dysentery (bloody diarrhea)
Helminths	*Ascaris lumbricoides*	Ascariasis (worm infecting the intestine)
Viruses	Hepatitis virus	Infectious hepatitis (jaundice)
Secondary pathogens		
Fungi	*Aspergillus fumigatus*	Aspergillosis (growth in lungs and other organs)
Actinomycetes	*Micromonospora spp.*	Farmer's lung (allergic responses in lung tissue)

3.7.2 Health risks from secondary pathogens

The contact or inhalation of air, containing a high density of spores of secondary pathogens can cause health hazards to the compost workers and users. An epidemiological study was conducted on compost workers at 9 sludge composting plants in USA to evaluate the associated potential health hazard (Clark *et al.* 1984). The results summarized in Table 3.7 indicate a higher health risk for the compost workers than for the control groups not involved in compost activities, nose and throat cultures positive for *Aspergillus fumigatus* were more common for these compost workers than for others. Since *Aspergillus fumigatus* can cause serious infections to lungs and other human organs, proper care must be taken to avoid the uptake of these spores.

The growth of *Aspergillus fumigatus* in composting may be controllable through moisture control management practice (Finstein *et al.* 1980) because fungi tend to thrive in material that is slightly too dry for profuse bacterial growth (Millner *et al.* 1977). However, routine monitoring for the presence of this type of fungus in compost piles should be carried out, and the compost workers must be informed of the potential infection from *Aspergillus fumigatus.*

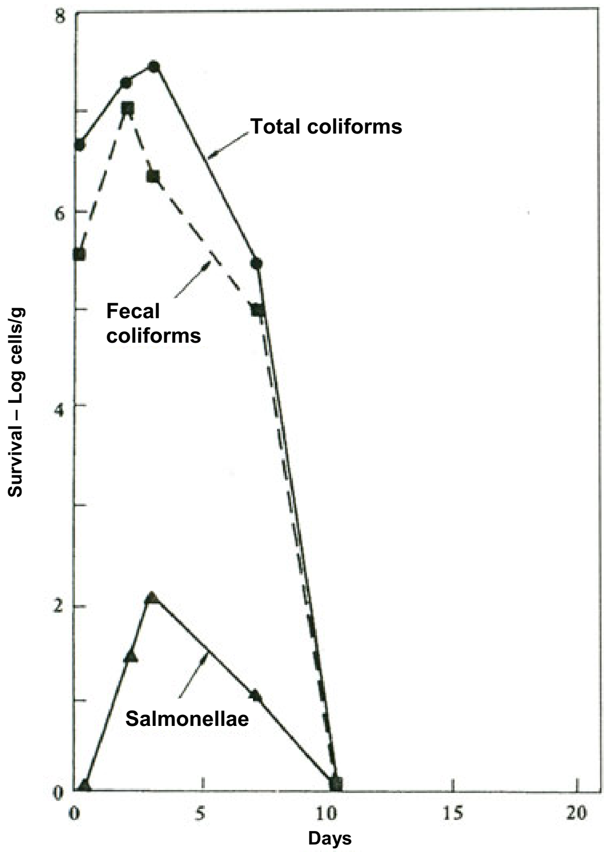

Figure 3.20 Destruction of Salmonellae, fecal coliforms, and total coliforms during composting by the BARC system (U.S. EPA 1985)

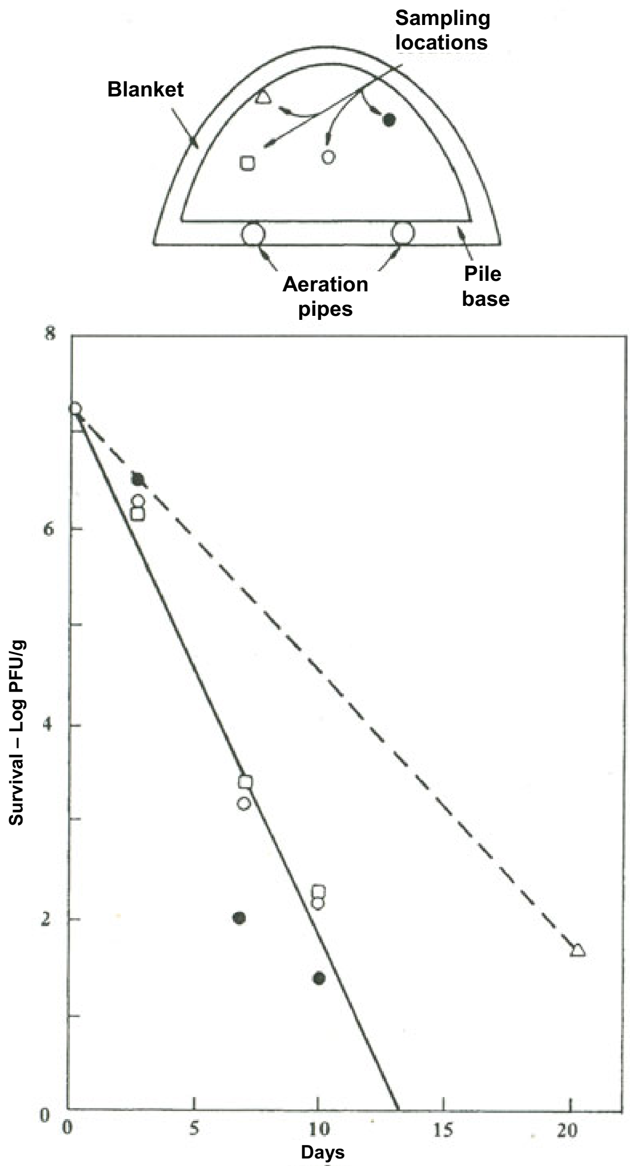

Figure 3.21 Destruction of F_2 bacteria virus during composting by the BARC system (U.S. EPA 1985)

Table 3.6 Thermal death points of some common pathogens and parasites

Organisms	Thermal death point
Salmonella typhosa	No growth beyond 46°C; death within 30 minutes at 55°C to 60°C
Salmonella spp.	Death within 1 hour at 55°C; death within 15 minutes to 20 minutes at 60°C
Shigella spp.	Death within one hour at 55 °C
Escherichia coli.	Most die within one hour at 55°C, and within 15 to 20 minutes at 60°C
Entamoeba histolytica cysts	Thermal death point is 68°C
Taenia saginata	Death within 5 minutes at 71°C
Trichinella spiralis larvae	Infectivity reduced as a result of one hour exposure at 50°C; thermal death point is 62-72°C
Necater americanus	Death within 50 minutes at 45°C
Brucella abortus or suis	Death within 3 minutes at 61°C
Micrococcus pyogenes var. aureus	Death within 10 minutes at 50°C
Streptococcus pyogenes	Death within 10 minutes at 54°C
Mycobacterium tuberculosis var.hominis	Death within 15 to 20 mins at 66°C, or momentary heating at 67°C
Corynebacterium diptheriae	Death within 45 minutes at 55°C

Table 3.7 Epidemiological effects to compost workers (Clark *et al.* 1984)

Excess of nasal, ear and skin infections (by physical exams) in compost and intermediate-exposed workers
Symptoms of burning eyes and skin irritation higher in compost and intermediate-exposed workers
Fungal colonies greater in cultures from compost workers
Legionella infections not associated with compost exposure but were higher among all workers exposure categories in Philadelphia-Camden area than in Washington, D.C., area
Evidence of higher white blood cell counts and hemolytic complement in compost workers
Higher antibody levels to compost-endotoxin in compost workers

Although such epidemiological study for compost workers in developing countries has not been reported, the health risks originating from the secondary pathogens should be similar or even greater than those reported in U.S.A. Therefore, skin contact with the composted materials should be avoided and proper measures, such as wearing gloves, boots and masks, are undertaken to prevent the inhalation of the spores of secondary pathogens, especially during turning of compost piles. The composting processes without pile turning, such as the BARC (Figure 3.14) and the Chinese (Figure 3.12) composting system, should pose less health hazards to the compost workers than those with pile turning.

3.8 UTILIZATION OF COMPOSTED PRODUCTS

Compost has been used as: a) fertilizer, b) soil conditioner, c) feed for fish in aquaculture, d) landfill material, e) horticultural medium on parkland, ornamental and recreational areas and in highway right-of-ways.

Screening, grinding, or combination of similar processes should be done to remove plastics, glass, and other materials from the compost that might be objectionable in its use. For some uses such as land filling and land reclamation, compost needs not be finished or processed further. For general agriculture/aquaculture, a coarse grind is satisfactory, whereas for horticulture and luxury gardening, the compost product must be finer. Compost to be used as fertilizer or soil conditioner is usually mixed with chemical fertilizers to make its nutrient contents suitable for crop growth. A schematic diagram of compost fertilizer production process is given in Figure 3.22.

3.8.1 Utilization as fertilizer and soil conditioner

Compost can improve overall soil fertility through the addition of organic matter and plant nutrients, and modify the soil pH. The long-term effect on soil fertility is also important. The result is that soil erosion can be reduced, the water retention capacity raised, the soil structure improved, and subsequently, vegetation can be established quickly.

The utilization of composted municipal wastes as fertilizers and soil conditioners will depend on three principal factors:

- Socio-economic considerations,
- Product quality, and
- Soil and plant responses

Socio-economic considerations

Socio-economic factors relate to health regulations, state laws regarding the sale of fertilizers or soil conditions, public acceptance, and marketing and distribution.

The distribution and utilization of composts produced from sewage sludge or refuse may need regulations that will require stabilization, pathogen reduction, and chemical analysis. The general public is more attuned to acceptance of composted sludges or refuses than unstabilized and potentially malodorous materials. If the application of chemical fertilizer is cheap, subsidized or practiced for long time, then the farmers will be reluctant to use compost products as fertilizer. The extent of utilization of composts will depend on the type of market and its proximity to the processing facility. Transportation costs and distance to markets will affect product value and its potential use.

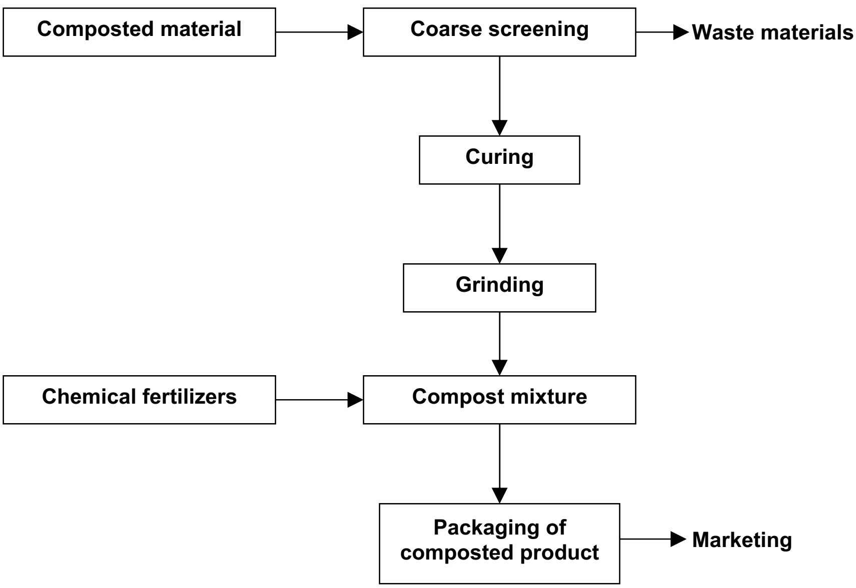

Figure 3.22 Flow chart of compost fertilizer production process

Product quality

The compost quality is greatly dependent on the chemical and physical characteristics of the raw materials, and on the processing system used to produce it. N, P and K are essential plant micronutrients (the higher the content of these elements, the greater the fertilizer value of the compost). Most of the N in the compost in an organic form and must be mineralized (such as through curing) to inorganic ammonium or nitrate before it is available to plants. Composted organic wastes function as slow-release N fertilizers when applied to soil. The K content of sludge compost is usually low (0.5%) because it is water soluble and remains in the effluent after wastewater treatment. However, in refuse compost the level of K may exceed 1 percent. The N, P and K values of compost do not only depend on the type of materials composted but also the initial C/N ratio of those materials.

Table 3.8 shows the composition of compost produced from municipal refuse of Bangkok city, Thailand. The percentages of N, P, K contents were 2.58, 1.67, and 0.58, respectively, which are several times lower than those present in chemical fertilizers. This compost thus needs to be mixed with chemical fertilizers prior to being used as fertilizer.

Table 3.8 Composition of compost produced from municipal refuse

Items	**% of composition (based on dry solids)**
Total-N	2.58
Total-P (P_2O_5)	1.67
Total-K (K_2O)	0.58
Magnesium (Mg)	0.49
Calcium (Ca)	6.20
Sulfur (S)	0.37
Iron (Fe)	4.39
Manganese (Mn)	0.16
Copper (Cu)	0.09
Zinc (Zn)	0.30
Baron (B)	0.051
Molybdinum (Mo)	0.001
Chlorine (Cl)	0.66
Moisture Content	23.86
pH	7.2 (dimensionless)

Source: The office of Bangkok municipal fertilizer (personal communication)

An experiment was carried out at AIT by composting night soil, water hyacinth and leaves (compositions are shown in Table 3.9) with different initial C/N ratios (Table 3.10). The method of composting employed was similar to that shown in Figures 3.11 and 3.12. The percent N, P and K of the composted products were found to be highest when C/N ratio of the mixture was 20 (Table 3.11) (Polprasert 1984). It is apparent the magnitude of increase in N, P and K percentages in the composted products was related to the initial characteristics of the composting materials and the percent loss of volatile solids after composting.

Organic chemicals such as pesticides, PCB's and heavy metals may be present in some wastes in sufficiently high concentrations to make the compost undesirable for land application.

Soil and plant response

Composts can be considered as fertilizers rich in organic matter. The organic matter is an excellent soil conditioner because it has been stabilized, decomposes slowly and thus remains effective over a longer period of time. Composts improve soils' physical properties as evidenced by increased water content and water retention; enhanced aggregation; increased soil aeration, soil permeability, and water infiltration; and decreased surface crusting. The greatest improvement in soil physical properties occurs in sandy and clayed soils.

Table 3.9 Nutrient contents of nightsoil, water hyacinth and leaves (dry weight basis)

Raw materials	Carbon (C) (%)	Nitrogen (N) (%)	Phosphorus (P) (%)	C/N Ratio
Nightsoil	54.1	3.6	0.9	15.2
Water hyacinth	45	2.9	0.5	15.8
Leaves	49.9	0.8	0.2	60.8

From Polprasert (1984); reproduced by permission of Pergamon Books Ltd

Table 3.10 Percentage of raw materials required in preparing compost piles (dry weight basis)

	Initial C/N ratio		
Raw materials	20	30	40
Nightsoil, (%)	14.4	10.9	7.3
Water hyacinth, (%)	57.4	25.4	10.9
Leaves, (%)	28.2	63.7	81.8
Water hyacinth: Nightsoil ratio	80:20	70:30	60:40

From Polprasert (1984); reproduced by permission of Pergamon Books Ltd

There are two principle objectives in applying sludge compost as a source of N for crops: to supplement the amount of potentially available N, and to ensure that the level of N applied as compost does not greatly exceed that necessary for attainable crop yields. Based on the N requirements of different crops (Table 8.7), the application rates will be different and the rates should be able to produce maximum growth and yield.

Table 3.11 Average nutrient contents (dry weight basis) of compost piles at the starting period and during the 30-60 days of composting

	Initial C/N ratio					
	20		30		40	
Nutrients	Starting period	30-60 days of composting	Starting period	30-60 days of composting	Starting period	30-60 days of composting
% N	2	2.2	1.3	1.9	1.3	1.9
% P	0.3	0.6	0.2	0.4	0.3	0.3
% K	1	1	0.6	0.6	0.6	0.6

From Polprasert (1984); reproduced by permission of Pergamon Books Ltd.

Table 3.12 Fish Yields from compost fed ponds (Edwards *et al.* 1983)

Experiment number	Pond number	Compost feeding rate, kg COD/(ha-yr)	Fish yield, kg /pond per 6 months	Extrapolated fish yield, kg/(ha-yr)
1	1	50 [a]	26.5	2,840
	2	0	7.6	820
	3	50 [b]	51.9	5,570
	4	0	8.15	875
2	1	25 [b]	15.7	1,510
	2	100 [b]	32.2	3,090
	3	0	6.6	630
	4	50 [b]	30.2	2,900
3	1	25 [b]	36.1	3,530
	2	50 [b]	35.9	3,500
	3	100 [b]	57.7	5,640
	4	0	11.2	1,100

[a] Compost whose initial C/N ratio was 30
[b] Compost whose initial C/N ratio was 20

3.8.2 Utilization as feed for fish

In waste recycling through aquaculture, herbivorous fish species (e.g. Tilapia) feeding on phytoplankton are commonly used. The addition of compost to fish ponds could increase the growth of phytoplankton, and will increase the fish growth and yield.

A preliminary experiment was carried out at AIT on Tilapia ponds fed with the composts whose characteristics are given in Table 3.11. The fish ponds were earthen, each having a working dimension of 20 x 10 x 1 m^3, length x width x depth. Three experimental runs, each lasting 6 months were carried out on 4 fish ponds. In experiment 1, ponds 2 and 4 served as control without compost feeding. Although the compost feeding rate for ponds 1 and 3 was 50 kg COD/(ha-day), the compost materials fed were obtained from the compost piles where initial C/N ratios were 30/1 and 20/1, respectively. Consequently, because of the higher nutrients content of the compost pile with the initial C/N ratio of 20/1 (Table 3.11), the fish yield in pond 3 was almost double of that in pond 1, while ponds 2 and 4 without compost feeding had fish yields several times lower than those of the other two ponds (Table 3.12). Based on these results, the compost materials used in experiments 2 and 3 were obtained from the compost piles with the initial C/N ratio of 20/1.

The data from Table 3.12 showed that the compost of nightsoil mixed with water hyacinth and vegetable leaves added to fish ponds increase the fish yield considerably and the amount of fish yields were almost proportional to the rate of compost feeding. Also these experimental results strongly indicated the technical feasibility of using composted nightsoil as feed for Tilapia growth. More details of the waste fish ponds are given in chapter 6.

The public health hazard resulting from this practice is considered to be much lower than the direct feeding of septic tank sludge or nightsoil to fish ponds. This is because most of the enteric microorganisms had been inactivated by heat during composting, and the remaining in the compost, when applying to fish ponds, would be diluted and, eventually, subject to natural die-off. However, in areas where certain helminthic diseases are endemic, care should be taken to control the transmission of these helminths, whose life cycle include pond fauna such as snails and/or fish as their intermediate hosts.

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3.10 EXERCISES

3.1 You are to conduct a batch composting experiment at home using raw materials generated in your home. Prepare a report describing the composition and characteristics of the organic wastes used as raw materials, types of composting (aerobic, anaerobic, aeration or pile turning, etc), temperature profiles, composting period, and changes (physical, chemical, biological characteristics) observed in the compost materials.

3.2 You are to conduct a survey of fertilizer usage in your country. Then estimate the amount of compost fertilizer that can be produced from the organic wastes, and calculate economic savings that could be achieved from usage of the compost fertilizer.

3.3 You are to conduct a public opinion survey to assess social acceptability of the usage of compost fertilizer in your community. The survey is to be done through questionnaire in which you (or a group of colleagues) need to set up suitable questions. The main aim of the survey is to find out means to increase public acceptability of the compost fertilizer.

3.4 A farm in Cambodia has 10 beef cattle. The cattle manure is to be composted together with rice straw, and the composted product used as fertilizer. The composting is carried out one batch each month. From the data in Tables 2.7 and 3.1, estimate the quantity of rice straw needed to mix with the cattle manure to obtain a C/N ratio of 25/1. Other data necessary for the estimation are as follows:

Manure:	
Total solids	= 10%
Rice straw:	
C/N ratio	= 80/1
Moisture content	= 30%
Bulk density	= 150 kg/m^3
N content	= 0.2% of dry weight

3.5 In Exercise 3.4, calculate the initial moisture content of the manure-straw mixture. What would you suggest if the moisture content is greater than 70%?

3.6 A sludge contains 70% of volatile portion (dry weight basis) and 60% of this volatile portion is biodegradable. The chemical composition of the volatile portion is $C_{10}H_{19}O_2N$. Calculate the weight and volume of air required to oxidize 1 kg of the sludge. Assume that the nitrogen is first converted to ammonia (NH_3) and then to nitrate (NO_3^-). Air contains 23% O_2 by weight with a specific weight of 1.2 kg/m^3 at 25°C and 1 atmospheric pressure.

3.7 Compare the advantages and disadvantages of aerobic composting and anaerobic composting?

3.8 What measures should be taken in using the composted products as soil conditioner or fertilizer in order to minimize the health risk?

3.9 The Bangkok city, Thailand, produces 200 tons (wet weight) of septage daily. This septage, whose C/N ratio is 15/1, contains 10% total solid (TS), volatile solids (VS) are 90% of TS, and the bulk density is 1.1 kg (wet weight)/L.

Sawdust is to be mixed with the above septage to adjust the mixture C/N ratio to be 30/1 before composting. Characteristics of saw dust are C/N ratio = 70/1, moisture content = 40%, N content = 0.1% (of dry weight), and the bulk density is 0.1 kg (wet weight)/L

a) Determine the amount of saw dust, in m^3/day, needed to be mixed with the Bangkok septage to adjust the C/N ratio to be 30/1, and the corresponding moisture content of the mixture.
b) Suppose windrow composting is to be employed to compost the mixture in (a) and the composting periods for first-stage composting and maturation are 5 and 10 days, respectively.

Determine the dimension (length × width × depth) of the windrow composting pile(s). Also suggest suitable operation procedures to achieve optimum composting efficiency. (Note: 1 ton = 1000 kg)

3.10 A municipality in Vietnam plans to employ a continuous compost reactor to stabilize its garbage and to produce compost fertilizer for use in public parks. The garbage characteristics are as follows:

Total wet weight (TWW)	= 2,000 kg/day
Bulk density	= 1.2 kg/L

Total solids (TS) content	= 20% of TWW
Organic compound (as $C_{10}H_{19}O_2N$)	= 50% of TS
Fecal coliforms	= 10^6 no./100 g
Bacteriophages	= 10^4 no./100 g

For continuous compost reactor:

Detention time	= 1 day
Temperature inside reactor	= 45°C
TS of composted product	= 50%

You are to determine the follows:

a) Size and dimensions of this continuous compost reactor suitable for treating this garbage. Draw schematic diagram of this continuous compost reactor.
b) The amount of composted product (in kg/day) that needs to be recycled to maintain the optimum TS content of the compost mixture of 40% at the inlet of the continuous compost reactor. Assuming that bulk density of the composted product and the compost mixture is also 1.2 kg/L. (See Figure 3.5)
c) The amount of air needed to be applied to this continuous compost reactor to compost the garbage. Assume that the following equation is applicable.

$$C_{10}H_{19}O_3N + 12.5O_2 \rightarrow 10CO_2 + 8H_2O + NH_3$$

Note: Air contains 20% O_2 by weight and specific weight of air is 1.2 g/L at 25°C and 1 atmosphere.

d) Based on the public health and scientific point of view, discuss whether the composted product of this continuous compost reactor is suitable for use as fertilizer give the reasons (See Figure 3.1)

4

Biofuels Production

With increasing population growth (Figure 1.1) and energy consumption (Figure 1.2), there have been a lot of interests worldwide to develop alternative sources of energy to supplement the heavy demands on natural oil and gases. Biogas (also called 'marsh gas'), a by-product of anaerobic decomposition of organic matters (Equation 2.3), has been considered as an alternative source of energy. The biogas can be used at small family units for cooking, heating and lighting, and at larger institutions for heating or power generation. Another potential source of renewable energy is ethanol, a liquid form of biofuel, which can be produced from fermentation of organic wastes such as sugarcanes, molasses, cassava and corn etc. Besides its current use as fuel, ethanol is also widely used in the chemical, pharmaceutical and cosmetic industries.

The common raw materials used for biogas generation are often defined as 'waste materials', e.g. human excreta, animal manure, sewage sludge, and vegetable crop residues, all of which are rich in nutrients suitable for the growth of anaerobic bacteria. Although some of the above materials can be used directly as fuels and fertilizers, they could be used for biogas production, as illustrated in Figure 4.1, to gain some additional heat value (from the biogas) while the other benefits are still retained. Depending on the composition of the raw materials, organic loading applied to the digestor and time and temperature of anaerobic decomposition, some variations in the composition of biogas can be noticed, but approximately it conforms to the following:

Methane	(CH_4)	55-65 %
Carbon dioxide	(CO_2)	35-45 %
Nitrogen	(N_2)	0.3 %
Hydrogen	(H_2)	0-1 %
Hydrogen sulphide	(H_2 S)	0-1 %

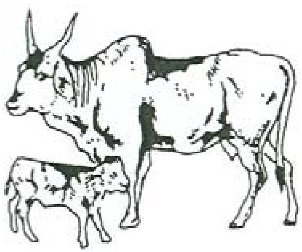
Of the different gases produced, CH_4 is the desirable gas, because it has a high calorific value (≈ 9000 kcal/m^3, equivalent to 13 kcal/g or 211 kcal/gmole at standard temperature and pressure.); the approximate heat value of the biogas is 4,500-6,300 kcal/m^3, depending on the contents of other gases besides CH_4.

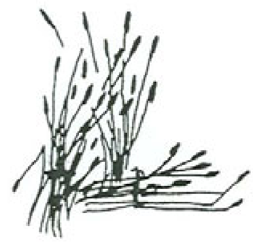
The three main types of biomass raw materials suitable for ethanol production are: (a) sugar containing materials (such as sugarcanes, molasses and sweet sorghum etc); (b) starch- containing materials (such as cassava, corn and potato etc); and (c) cellulose materials (such as wood and agricultural residues etc). Among the above, because the sugar content is already in the fermentable, simple sugar form, the sugar containing materials can be readily fermented to produce ethanol. For the other two raw materials (the starch and cellulosic materials), the carbohydrates have to be biochemically converted into sugars first before being fermented by yeasts into ethanol. Finally, the fermented ethanol needs to be separated from water and other fermentation products by distillation prior to application. The calorific value of ethanol is 7.13 kcal/g or 328 kcal/gmole. Description of the biogas and ethanol production technology is given below.

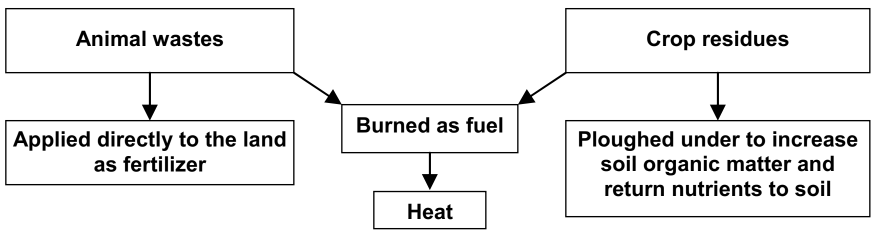
4.1 OBJECTIVES, BENEFITS AND LIMITATIONS OF BIOGAS TECHNOLOGY

The main purposes and benefits of biogas technology are classified as follows:

Original uses:







Addition of methane generation:

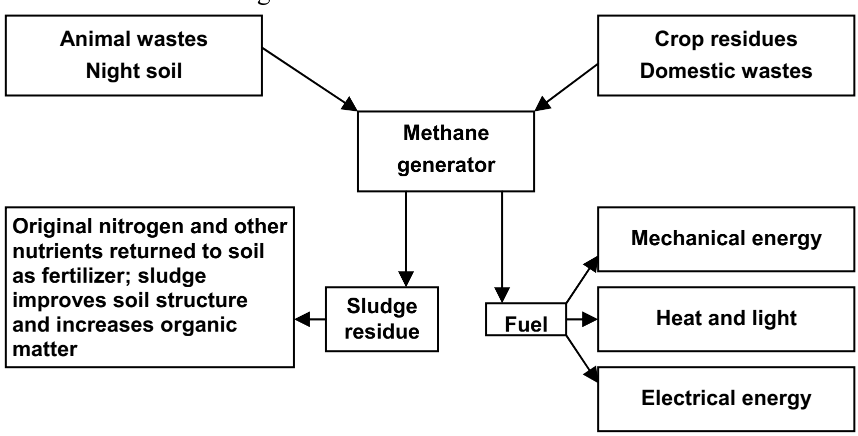


Figure 4.1 Impact of anaerobic fermentation on use of organic wastes (NAS 1977)

4.1.1 Production of an energy source

The production of an energy resource (biogas) from anaerobic digestion of organic wastes is the most tangible benefit of biogas technology. Practicing biogas production in rural areas can have several advantages such as relieving demand on electricity, coal, oil and firewood, and those associated with administrative/distribution network. Organic matters required for biogas production are abundant and easily available. Decreasing the demand for firewood spares the forest and furthers afforestation efforts.

4.1.2 Waste stabilization

The biological reactions occurring during anaerobic digestion in the biogas digester reduce the organic content of waste materials by 30 - 60% and produce a stabilized sludge which can be used as a fertilizer or soil conditioner.

4.1.3 Nutrient reclamation

The nutrients (N, P and K) present in the wastes are usually in complex organic forms that are difficult for the crops to uptake. After digestion, at least 50% of the nitrogen present is as dissolved ammonia which can be nitrified to become nitrate when applied to crops (Equation 3.5) or is readily available to crops. Thus digestion increases the availability of nitrogen in organic wastes above its usual range of about 30-60%. The phosphate and potash contents are not decreased and their availability of around 50% and 80%, respectively, are not changed during digestion. Anaerobic digestion does not lose or destroy any of the nutrients from domestic and farm wastes, but makes them more available to plants. In addition to being used as a fertilizer, the biogas digester slurry also acts as a soil-conditioner and helps in improving the physical properties of the soil. The application of digester slurry to unproductive soils would eventually improve the soil quality, or the useless lands can be reclaimed.

4.1.4 Pathogen inactivation

During the digestion process, the waste is kept without oxygen for a long period of time (15-50 days), at about 35°C. These conditions are sufficient to inactivate some of the pathogenic bacteria, viruses, protozoa and helminth ova.

However, biogas technology has some drawbacks. When compared with other alternatives, such as composting, biogas production can be construed as the only major advantage of this technology. Other advantages, e.g. waste stabilization and pathogen inactivation, are fulfilled better by composting (a comparative analysis between biogas technology and composting is summarized in Table 4.1). Other limitations include high capital cost, seasonal variations in gas production, operation and maintenance problems.

Because pathogen inactivation in anaerobic digesters is generally incomplete and the digested slurry is in liquid form, special care has to be taken in the handling and reuse of the digested slurry. Perhaps, this is a reason for the negative attitude towards the use of human nightsoil for biogas production.

Table 4.2 summarizes some of the advantages and disadvantages of the use of biogas technology as a method of processing biodegradable organic wastes.

Table 4.1 Comparative analysis of biogas technology and composting (Adapted from Tam and Thanh 1982)

Operating conditions	Composting (aerobic/anaerobic)	Biogas technology
Materials added to nightsoil or animal manure for C/N ratio and moisture adjustments.	Vegetation	Water + vegetation
Temperatures	50 - 70°C	Ambient
Period of operation	6-8 weeks (including maturation and curing)	4-8 weeks
Nitrogen loss	Low to high	Low to medium
Space required	Same	Same
Modes of operation	Range from traditional to complicated	Complicated
Odor	Problem for open system	Less problem due to closed system
End products	Composted material	Digested slurry (and CH_4 gas)
Weight	Reduced due to water loss	Increased in density due to biomass production
Water content	40 - 50 %	88 - 92 %
Humus content	Abundant	Less than composted products
Pathogen destruction	Good	Moderate
Transport	Easier (solid matter)	More difficult (liquid matter)
Further handling	Not necessary	Drying usually needed
Storage	Easy, little loss of nitrogen	Difficult. With possible loss of nitrogen

Table 4.2 Advantages and disadvantages of biogas technology (NAS 1977)

Advantages	Disadvantages
Produces large amount of methane gas. Methane can be stored at ambient temperature.	Possibility of explosion.
Produces free-flowing, thick, liquid sludge.	High capital cost. (However, if operated and maintained properly, the system may pay for itself.)
Sludges are almost odorless, odor not disagreeable.	May develop a volume of waste material much larger than the original material, since water is added to substrate. (this may not be a disadvantage in the rural areas of developing countries where farm fields are located close to the village, thus permitting the liquid sludge to be applied directly to the land, serving both for irrigation and as fertilizer.)
Sludge has good fertilizer value and can be used as a soil conditioner.	Liquid sludge presents a potential water pollution problem if handled incorrectly.
Reduces organic content of waste materials by 30-50 percent and produces a stabilized sludge for ultimate disposal.	Maintenance and control are required.
Weed seeds are destroyed and pathogens are either destroyed or greatly reduced in number.	Certain chemicals in the waste, if excessive, have the potential to interfere with digester performance. (However, these chemicals are encountered only in sludges from industrial wastewaters and therefore are not likely to be a problem in a rural village system.)
Rodents and flies are not attracted to the end product of the process.	Proper operating conditions must be maintained in the digester for maximum gas production.
Access of pests and vermin to wastes is limited.	Most efficient use of methane as a fuel requires removal of impurities such as CO_2 and H_2S, particularly when the gas is to be used in internal-combustion engines.
Provides a sanitary way for disposal of human and animal wastes.	
Helps conserve scarce local energy resources such as wood.	

4.2 BIOCHEMICAL REACTIONS AND MICROBIOLOGY OF ANAEROBIC DIGESTION

The anaerobic digestion of organic material is, chemically, a very complicated process involving hundreds of possible intermediate compounds and reactions, each of which is catalyzed by specific enzymes or catalysts. However, the overall chemical reaction is often simplified to:

$$\text{Organic matter} \xrightarrow[\textit{digestion}]{\textit{Anaerobic}} CH_4 + CO_2 + H_2 + NH_3 + H_2S \tag{4.1}$$

In general, anaerobic digestion is considered to occur in the following stages:

1) Liquefaction or polymer breakdown
2) Acid formation, and
3) Methane formation

Figure 4.2 shows the main intermediate compounds formed during anaerobic decomposition of protein, carbohydrate, and fat. Descriptions of reactions occurring in each of the three stages are as follows:

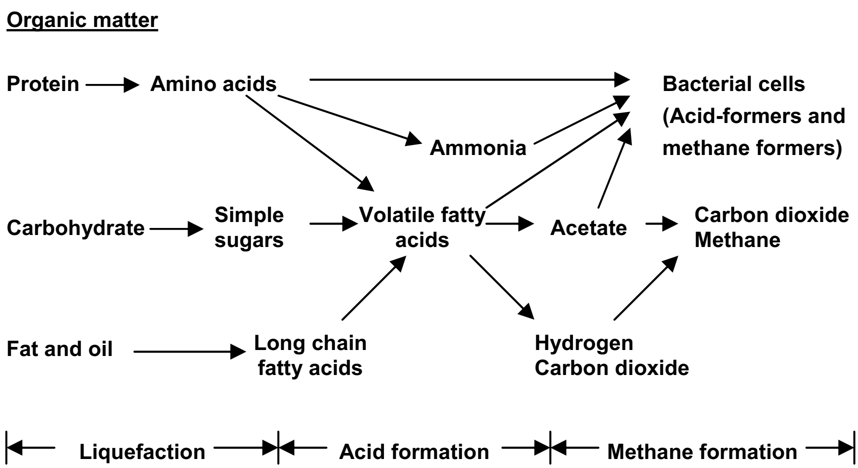


Figure 4.2 Anaerobic digestion of organic compound

Stage 1: Liquefaction

Many organic wastes consist of complex organic polymers such as proteins, fats, carbohydrates, cellulose, lignin, etc., some of which are in the form of insoluble solids. In this stage, these organic polymers are broken down by extracellular enzymes produced by the hydrolytic bacteria, and dissolved in the water. The simple, soluble, organic components (or monomers) which are formed are easily available to the acid producing bacteria. It is difficult to distinguish this stage from what is known as stage 2 (acid-formation stage), for some molecules will be absorbed without further breakdown and can be degraded internally.

As shown in Figure 4.2, the hydrolysis reactions occurring in this stage will convert protein into amino acids, carbohydrate into simple sugars and fat into long-chain fatty acids. However the liquefaction of cellulose and other complex compounds to simple monomers can be the rate-limiting step in anaerobic digestion, since this bacterial action is much slower in stage 1 than in either stage 2 or 3 (NAS 1977). Hydrolysis rate is dependent on substrate and bacterial concentrations as well as on the environmental factors such as pH and temperature.

Stage 2: Acid formation

The monomeric components released by the hydrolytic breakdown that occurs during the stage-1 bacterial actions are further converted to acetic acid (acetates) and H_2/CO_2 by the acetogenic bacteria in this stage. Volatile fatty acids are produced as the end products of bacterial metabolism of protein, fat and carbohydrate; in which acetic, propionic, and lactic acids are the major products. Carbon dioxide and hydrogen gas are also liberated during the carbohydrate catabolism. Methanol and other simple alcohols are other possible by-products of carbohydrate breakdown. The proportion of these different substrates produced depends on the flora present as well as on the environmental conditions.

Stage 3: Methane formation

The products of stage 2 are finally converted to CH_4 and other end products by a group of bacteria called methanogens. Methanogenic bacteria are obligate anaerobes whose growth rate is generally slower than those bacteria in stages 1 and 2.

The methanogenic bacteria utilize acetic acid, methanol, or carbon dioxide and hydrogen gas to produce methane. Acetic acid or acetate is the single most important substrate for methane formation, with approximately 70% of the methane produced being from acetic acid. The remaining methane comes from carbon dioxide and hydrogen. A few other substrates can also be utilized, such as formic acid, but these are not important, since they are not usually present in anaerobic fermentation. The methanogenic bacteria are also dependent on the stage-1 and -2 bacteria to provide nutrients in a utilizable form. For example, organic nitrogen compounds must be reduced to ammonia to ensure efficient nitrogen utilization by the methanogenic bacteria.

The reactions of methane formation in stage 3 are most important in anaerobic digestion. Besides producing CH_4 gas, the methanogens also regulate and neutralize the pH of the digester slurry by converting the volatile fatty acids into CH_4 and other gases. The conversion of H_2 into CH_4 by the methanogens helps reduce the partial pressure of H_2 in the digester slurry which is beneficial to the activity of the acetogenic bacteria. If the methanogenic bacteria fail to function effectively there will be little or no CH_4 production from that digester and waste stabilization is not achieved because the organic compounds will be converted to only volatile fatty acids, which can cause further pollution if discharged into a water course or on land. Since the methanogenic bacteria are obligate anaerobes, their growth is inhibited even by small amounts of oxygen and it is essential that a highly reducing environment be maintained to promote their growth. The methane bacteria are also sensitive to other environmental factors which are discussed in detail in section 4.3.

The current understanding of the microbiology of anaerobic digestion is illustrated in Figure 4.3. There are four main groups of bacteria involved in the process namely (Brown and Tata 1985):

1) Acid-forming (hydrolytic and fermentative) bacteria,
2) Acetogenic (acetate and H_2-producing) bacteria,
3) Acetoclastic (methane-forming) bacteria, and
4) Hydrogen-utilizing methane bacteria

Acid-forming and acetogenic bacteria are collectively called non-methanogenic bacteria in which the major bacterial species are given in Table 4.3. The acetoclastic and hydrogen-utilizing methane bacteria are collectively called methanogenic bacteria as shown in Table 4.4.

The acid-forming bacteria are involved in the hydrolysis and break down of complex organic compounds into simple products such as CO_2, H_2 and other volatile fatty acids via two main pathways (Gunnerson and Stuckey 1986):

$$\text{Substrate} \longrightarrow CO_2 + H_2 + \text{acetate} \quad (4.2)$$
$$\text{Substrate} \longrightarrow \text{propionate} + \text{butyrate} + \text{ethanol} \quad (4.3)$$

The products from Equation 4.2 can be utilized directly by the acetoclastic bacteria (Equation 4.4) and the hydrogen-utilizing methane bacteria (Equation 4.5) to produce CH_4.

$$\underset{\text{(acetate)}}{CH_3COO^-} + H_2O \longrightarrow CH_4 + H\,CO_3^- + \text{energy} \quad (4.4)$$
$$4H_2 + H\,CO_3^- + H^+ \longrightarrow CH_4 + CO_2 + \text{energy} \quad (4.5)$$

McInerney and Bryant (1981) reported that the reaction in Equation 4.2 will predominate in a digester having a low H_2 partial pressure. At high H_2 partial pressure Equation 4.3 will be favoured with the formation of volatile fatty acids having more than two carbon atoms (e.g. propionate and butyrate) and ethanol. These products are converted further to methanogenic substrate such as acetate, H_2 and CO_2 by the acetogenic bacteria through the acetogenic dehydrogenation reaction. Some acetogenic bacteria can also convert H_2 and CO_2 to acetate through the acetogenic hydrogenation (Figure 4.3).

Brown and Tata (1985) reported that the acetoclastic bacteria have a longer generation time than the acid-forming bacteria (i.e. 2-3 days vs. 2-3 hours at 35°C, under optimum conditions). Thus, anaerobic digesters should not receive too high organic loadings as the acid forming bacteria will produce volatile fatty acids faster than the rate at which the acetoclastic bacteria can utilize them.

It is currently known that the growth of acetogenic bacteria is sensitive to the H_2 partial pressure in the anaerobic digestion system (McInerney and Bryant 1981). If the H_2 partial pressure is above 0.0001 atmospheres, the Equation 4.3 reaction will be formed and the production of acetate will be minimized. Since about 70% of CH_4 is formed by the reaction in Equation 4.4 (as previously stated), the rate of biogas production will be decreased. Note: partial pressure of a gas is the percent by volume of that gas in the mixture. The H_2 partial pressure of 0.0001 is equivalent to 0.01% or about 100 ppm.

It appears that the reaction in Equation 4.5 is important to the anaerobic digestion process because it removes H_2 gas from the system and helps maintain the low H_2 partial pressure. Mosey (1982) suggested that it may be more useful to monitor the H_2 partial pressure in a digester with a simple electronic instrument, to control the anaerobic digestion process. However, a malfunctioned digester might also be caused by other environmental factors such as pH decrease and overloading, etc.; these factors are described in section 4.3.

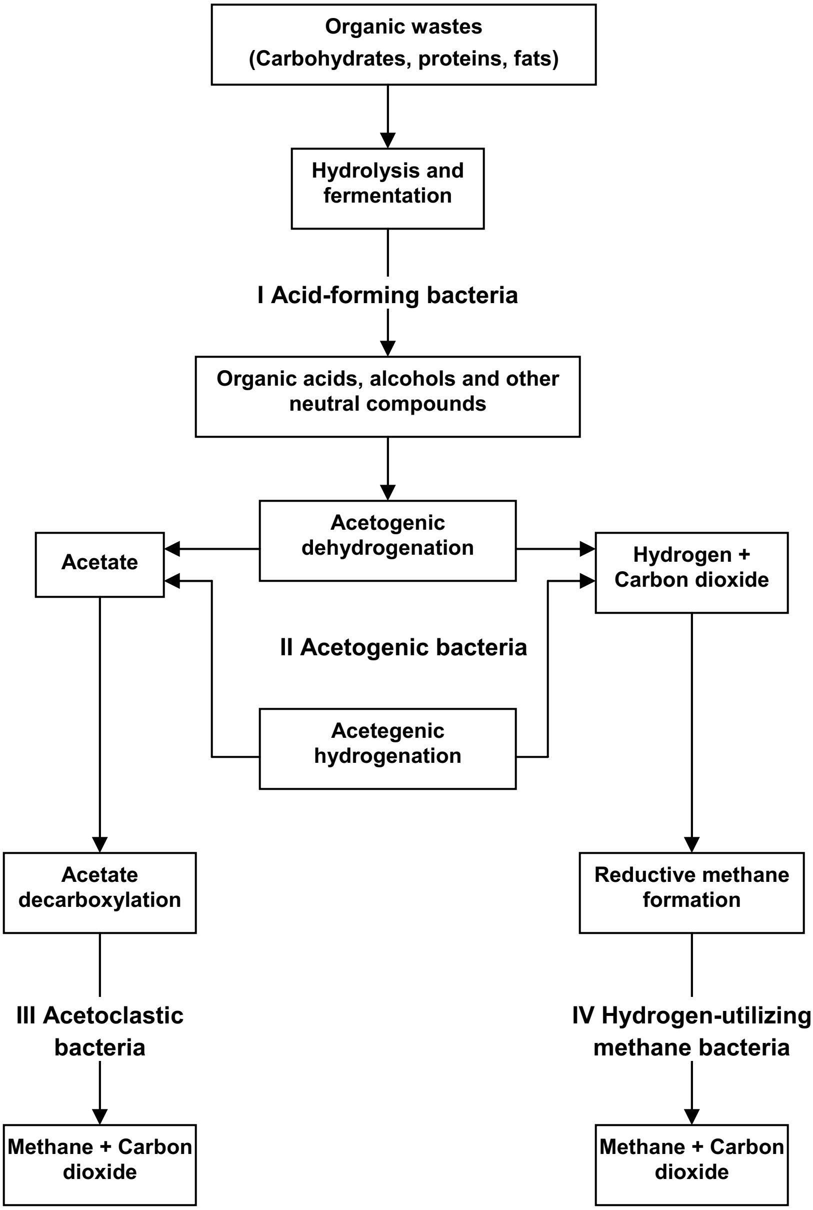


Figure 4.3 Biomethanation of organic wastes (Brown and Tata 1985)

Table 4.3 Non-methanogenic bacteria

Bacterium	Substrate	Product
1. Cellulose-splitting Acetivibrio cellulolyticus *Bacteroides fibrisolvens* *B. succinogenes* *Clostridium cellulovorans* *Cl. dissolvens* *Cl. omelianskii* *Cl. papyrosolvens* *Cl. populeti* *Cl. thermocellum* *Neocallimastix frontalis* *Ruminococcus flavefaciens*	Cellulose	Smaller compounds of low molecular weight, e.g. formate, acetate, succinate, lactate, H_2, CO_2, ethanol
2. Semi-cellulose-splitting *Bacteroides fibrisolvens* *B. ruminicola*	Semi-cellulose	Xylose, arabinose, galactose, mannose, formate, butyrate, lactate, H_2, CO_2, propionate, acetate, succinate
3. Starch-splitting *Bacterium butylicum* *Bacteroides spp.* Clostridium acetobutylicum *Lactobacillus spp.*	Starch	Acetobutanol, butyrate, acetate, H_2, glucose, maltose, oligosaccharides
4. Protein-splitting *Bacteroides amylophilus* *B. ruminicola* *Clostridium spp.*	Protein	Amino acids, organic acids, NH_3, H_2S
5. Fat-splitting *Alcaligenes spp.* *Bacillus spp.* *Micrococcus spp.* *Pseudomonas spp.* *Streptomyces spp.*	Fat and oil	Long-chain fatty acids
6. Acetogenic *Species of the Enterbacteriaceae and Bacillaceace families*	e.g. alcohol, butyric acid, aromatic acids, long-chain fatty acids	Acetate, H_2, CO_2

Sources: United Nations (1984); Smith *et al.* (1988); ESCAP (1975)

Table 4.4 Type species of methanogenic bacteria (Ferguson and Mah 1987)

Bacterium	Substrate
Methanobacterium alcaliphilum WeN4	H_2-CO_2
Methanobacterium bryantii M.O.H.	H_2-CO_2
Methanobacterium formicicum DSM 863	H_2-CO_2, formate
Methanobacterium thermoautotrophicum ΔH	H_2-CO_2
Methanobacterium uliginosum P2St	H_2-CO_2
Methanobacterium wolfei DSM 2970	H_2-CO_2
Methanobrevibacter arboriphilicus DH1	H_2-CO_2
Methanobrevibacter ruminantium M1	H_2-CO_2, formate
Methanobrevibacter smithii PS	H_2-CO_2, formate
Methanococcoides methylutens TMA-10	Methanol, trimethylamine[a]
Methanococcus halophilus INMI Z-7982	Methanol, trimethylamine[a]
Methanococcus jannaschii JAL-1	H_2-CO_2
Methanococcus maripaludis JJ	H_2-CO_2, formate
Methanococcus thermolithotrophicus DSM 2095	H_2-CO_2, formate
Methanococcus vannielii DSM 1224	H_2-CO_2, formate
Methanococcus voltae PS	H_2-CO_2, formate
Methaongenium aggregans MSt	H_2-CO_2, formate
Methanogenium bourgense MS2	H_2-CO_2, formate
Methanogenium cariaci JR1	H_2-CO_2, formate
Methanogenium marisnigri JR1	H_2-CO_2, formate
Methanogenium thermophilicum CR1	H_2-CO_2, formate
Methanolobus tindarius Tindari 3	Methanol, trimethylamine[a]
Methanomicrobium mibile BP	H_2-CO_2, formate
Methanomicrobium paynteri G-2000	H_2-CO_2
Methanoplanus limicola DSM 2279	H_2-CO_2, formate
Methanosarcina acetivorans C2A	H_2-CO_2, methanol, trimethylamine[a], acetate
Methanosarcina barkeri MS	H_2-CO_2, methanol, trimethylamine[a], acetate
Methanosarcina mazei S-6	Methanol, trimethylamine[a], acetate
Methanosarcina thermophila TM-1	Methanol, trimethylamine[a], acetate
Methanosphaera stadmanae MCB-3	Methanol plus H_2[b]
Methanospirillum hungatei JF1	H_2-CO_2, formate

Table 4.4 Type species of methanogenic bacteria (Ferguson and Mah 1987) (continued)

Bacterium	Substrate
Methanothermus fervidus DSM 2088	H_2-CO_2
Methanothrix concilii GP6	Acetate
Methanothrix soehngenii Opfikon	Acetate

[a] May also use mono- and dimethylamine
[b] Requires the combination of methanol and H_2

4.3 ENVIRONMENTAL REQUIREMENTS FOR ANAEROBIC DIGESTION

Anaerobic reactions in a digester can start quickly with the presence of a good inoculum or seed, such as digested sludge. During start-up or acclimation, the seed material should be added to the influent feed material in sufficient quantity, e.g. at least 50%. The seed volume can then be progressively reduced while increasing the proportion of the influent feed over a three- or four-week period. At the end of this period, the influent feed can be fed alone to the digester to support the growth of anaerobic bacteria. Solid content of the feed material should be about 5-10%, the remaining being water.

Like any other biological processes, anaerobic digestion is a multi-parameter controlled process, each individual parameter having overall control over the process either through their own effect on the system or interaction with other parameters. These parameters are described below:

4.3.1 Temperature

Temperature and its daily and seasonal variation have a pronounced effect on the rate of gas production. Generally two ranges of temperature are considered in methane production. These are mesophilic (25 - 40°C) and thermophilic (50 - 65°C) similar to those described in Chapter 3. The rate of methane production increases as the temperature increases, but there is a distinct break in the rise at around 45°C, as this temperature favours neither the mesophilic nor the thermophilic bacteria (Figure 4.4). However, no definite relation other than increasing rate of gas production (within certain limits) can be established. Below 10°C the gas production reduces drastically; therefore, operation below this level is not recommended due to limited amount of gas production (among other technical problems). Above 30 - 35°C, operation of the digester requires substantial amount of energy input for digester heating and this in turn will make the operation economically impractical. This suggests that mesophilic range provides the optimal operational range of temperature, although pathogen inactivation will be less than those to be achieved in the thermophilic range (Figure 3.1).

During winter period, heating of biogas digesters may be necessary so that growth of anaerobic bacteria, especially the methanogens, will be possible. The heating of a digester can be accomplished by heating the influent feeding materials (e.g. with the biogas produced) and feeding it to the digester, or by the recirculation of hot water through coils of pipe installed inside the digester. Other means to heat a digester include (Brown and Tata 1985):

- housing the digester in an enclosure lined with a thick transparent plastic film; the heat within the enclosure can be 5 - 10°C higher than the ambient temperature.
- designing the digester in such a way that water can be held on the roof of the digester and heated by solar radiation.
- insulating the digester with suitable materials available locally or by placing compostable material like leaves in an annular space built around the digester.

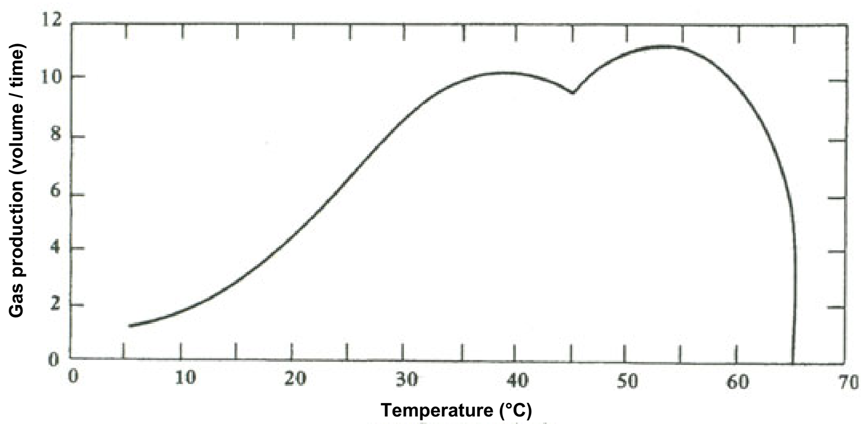


Figure 4.4 Effect of temperature on gas production (Price and Chermisinoff 1981)

4.3.2 pH and alkalinity

Operational range of pH in anaerobic digesters should be between 6.6 and 7.6, with the optimum range being 7 to 7.2. Although acid-forming bacteria can tolerate a pH as low as 5.5, the methanogenic bacteria are inhibited at such low pH values. The pH of a digester may drop to below 6.6 if there is an excessive accumulation of volatile fatty acids. Such an accumulation may occur when the organic loading rates are excessively high and/or when toxic materials are present in the digester, all producing inhibitory effects to the methanogenic bacteria.

Appropriate measures should be taken promptly when there is a lowering of pH in an anaerobic digester due to accumulation of volatile fatty acids or increase in H_2 partial pressure, and the rate of CH_4 production decreases. In general, the feeding of the digester should be stopped to allow the methanogens to utilize the accumulated volatile fatty acids and H_2 at their pace. When the optimal gas production rates are re-established, the normal loading of the digester can be resumed. In addition, the pH of the digester needs to be adjusted to neutrality by the addition of lime or other basic materials. If the alkalinity of the digester slurry is maintained within the range of 2,500 to 5,000 mg/L, a good buffering capacity is normally obtained in the digester.

4.3.3 Nutrient concentration

Most of the information available in this area has been obtained from studies of rumen bacteria. Energy for growth of most rumen bacteria is obtained through anaerobic fermentation of carbohydrates. Nitrogen is utilized for cell structure. To guarantee the normal biogas production, it is important to mix the raw materials in accordance with a proper C/N ratio. Bacteria use up carbon 25 - 30 times faster than they use nitrogen. Therefore, at this ratio of C/N (25-30/l) the digester is expected to operate at the optimal level of gas production, similar to that required for composting (Chapter 3). Importance of other elements such as P, Na, K and Ca in the gas production is also indicated. However, C/N ratio is considered the essential factor.

The C/N ratios of various organic wastes are given in Table 3.1. Since human nightsoil, animal manures and sewage sludge have C/N ratios lower than the optimum values; they may be mixed with other agricultural residues that have high C/N ratios. Examples of these residues are wheat straw, rice straw, water hyacinth and duckweeds, all of which are usually biodegradable, and can be made more so by physical size reduction (e.g. shredding) or by precomposting. However, problems can arise with these agricultural residues as they float to the top and forming a hard layer of scum on the slurry surface inside the digester (Polprasert *et al.* 1982)

When combination of organic wastes is considered for anaerobic digestion, Table 3.1 should be referred to select the proper combination and appropriate C/N ratio according to the method shown in Example 3.1.

4.3.4 Loadings

This term can be expressed as organic loading {kg COD or volatile solids (VS)/m^3-day} and hydraulic loading or retention time (HRT). A too-high organic loading will normally result in excessive volatile fatty acid production in the digester (sour condition) with a consequent decrease in pH, and adversely affecting the methanogenic bacteria. A too-low organic loading will not provide sufficient quantity of biogas for other uses and will make the digester size unnecessarily too large. Because organic materials feeding to anaerobic digesters are in semi-solid form, organic loading to a digester can be conveniently interpreted in terms of VS.

Section 4.4 describes the two main types of anaerobic digesters i.e. the dispersed-growth digesters (those employing dispersed-growth bacteria) and the attached-growth digesters (those employing attached-growth bacteria). Optimum organic loadings to dispersed-growth digesters have been reported to be 1-4 kg VS/(m^3-day) and 1-6 kg COD/(m^3-day); for attached-growth digesters, they are 1-15 and 5-30 kg COD/(m^3-day) for anaerobic filters and up-flow sludge blanket digesters, respectively (Barnet *et al.* 1978 and Brown and Tata 1985).

HRT has an equally significant effect on digester performance. Too short an HRT will not allow sufficient time for anaerobic bacteria, especially the methane-forming bacteria, to metabolize the wastes. Too long an HRT could result in excessive accumulation of digested materials in the digester, and construction of the digester too large in size. Similar to the organic loadings, an optimum HRT depends on the characteristics of influent feed materials and environmental conditions in the digesters. For dispersed-growth digesters, the optimum HRT falls within the range of 10-60 days; while for the attached-growth digesters, they are 1-10 and 0.5-6 days for anaerobic filters and up-flow sludge blanket digesters, respectively (Brown and Tata 1985).

It appears from the above information that the attached-growth digesters can be operated at higher organic loadings or shorter HRT than the dispersed-growth digesters. This advantage is attributed to the nature of attached-growth bacteria that attach to the media and/or stay in the digester for a long period of time. They are thus present in the digesters in high concentrations, not easily washed out/overflowed in the digester slurry, and are well acclimated to the incoming wastes. To increase the process performance or achieve higher loading rates, the dispersed growth digesters can have part of their slurry recycled back to the digesters in order to retain more active biomass and increase the solids retention time.

4.3.5 Presence of toxic compounds

For anaerobic digestion of organic wastes such as human excreta, animal manure and other agricultural residues, accumulation of volatile fatty acids, H_2 and undissociated ammonia are commonly associated with digester failure. The presence of molecular oxygen is also inhibitory to the methanogenic bacteria.

A list of common inhibitors to anaerobic digestion is given in Table 4.5. Inhibition caused by excess concentrations of certain ions can be counterbalanced by some other ions (antagonistic ions), while it can also be exacerbated by others (synergistic ions). Organic wastes containing those inhibitors as listed in Table 4.5 should be pre-treated or diluted so that the inhibitors' concentrations are below the inhibiting concentrations prior to being fed to anaerobic digesters

4.3.6 Mixing

Mixing of digester slurry is important to provide better contact between the anaerobic bacteria and the incoming organic wastes, so that biogas production is enhanced. It reduces the settling of solids or accumulation of digested solids at the bottom of the digester and helps to prevent/break-up scum formation at the slurry surface. For small-scale digesters, mixing of the digester's slurry can be accomplished manually as described in section 4.4. In large-scale digesters, mixing can be done mechanically by stirring and recirculation of the gas and/or the digested slurry.

4.4 MODES OF OPERATION AND TYPES OF BIOGAS DIGESTERS

There are different types of anaerobic digesters for experimental purposes, pilot plant investigations and actual field use. Their design, materials, system performance, price, etc. naturally vary a great deal. Operationally, it is required that air is excluded from the content of the digester, and sufficient volume is provided within the digester for the biological reactions to take place. Major modes of digester operation can be classified into three groups as follows:

Table 4.5 Inhibitors of biomethanation (U.S. EPA 1979)

Parameters	Inhibiting concentration (mg/L)
Volatile acids	>2,000 (as acetic acid)[a]
Ammonia nitrogen	1,500 - 3,000 (at pH>7.6)
Sulfide (soluble)[b]	>200; >3,000 toxic
Calcium	2,500 - 4,500; 8,000 strongly inhibitory
Magnesium	1,000 - 1,500; 3,000 strongly inhibitory
Potassium	2,500 - 4,500; 12,000 strongly inhibitory
Sodium	3,500 - 5,500; 8,000 strongly inhibitory
Copper	0.5 (soluble metal)
Cadmium	150[c]
Iron	1,710[c]
$Chromium^{+6}$	3
$Chromium^{+3}$	500
Nickel[d]	2

[a] Within the pH range of 6.6 to 7.4 and with adequate buffering capacity, volatile acids concentrations of 6,000 to 8,000 mg/L may be tolerated.
[b] Off-gas concentration of 6% is toxic.
[c] Millimoles of metal per kg of dry solids.
[d] Nickel promotes methane formation at low concentrations. It is required by methanogens.

4.4.1 Modes of operation

Batch operation

In this mode of operation the digester is filled completely with organic matter and seed inoculum, sealed, and the process of decomposition is allowed to proceed for a long period of time until gas production decreases to a low rate (duration of process varies based on regional variation of temperature, type of substrate, etc.), it is unloaded, leaving 10-20% as seed, then reloaded and operation continues. In this type of operation the gas production is expected to be unsteady and the production rate varying from high to low, and digestion failures due to shock load is not uncommon. This mode of operation, however, is suitable for handling large quantities of organic matter at distant intervals. It may need separate gas holders if a steady supply of gas is desired.

Semi-continuous operation

This involves feeding of the digester on a more regular basis. Feeding is done usually once or twice a day. The digested organic matter is also removed on the same time interval basis. This type of operation is suitable when there is a steady flow of organic matter. The digester volume will have to be large enough to serve both as a reactor and a gas storage tank. Total gas production per unit organic weight of organic matter loaded is usually high. Most of the operational biogas plants in the field are of this type.

Continuous operation

In this mode of operation the feeding and removal of organic matter take place at all times. The amount of material to be digested is kept constant in the digester by overflow or pumping. It has been used in treatment of liquid wastes or organic wastes with low solid concentrations. Continuous operation relies heavily on external energy inputs for pumping and mixing, and therefore has limited application in the areas where energy resources are of limited supply.

It should be noted, however, that seed inoculum is added at the beginning of the process of anaerobic digestion (start-up) and actual operation starts as soon as the microbial population establishes itself, and gas production plus percentage of methane gas in total gas production stabilize. In field implementation of anaerobic digestion, the animal manure itself acts as seed inoculum and the process may reach its stability within 20-30 days of operation (depending upon temperature, digester size and type of substrate).

4.4.2 Types of digesters

Various designs of biogas digesters for actual field operation range from a simple design to a sophisticated one. It is generally known that, the increased level of sophistication in design would result in a higher demand on manpower with appropriate skills, which is normally in short supply. Furthermore, more advanced designs increase the cost associated with construction and operation, with small apparent increase in the level of gas production.

Double-stage digesters (i.e. first-stage for acid formation and second-stage for CH_4 formation) are mostly designed for experimental purposes to provide more insight into, and an understanding of, the complex nature of the anaerobic process. Single-stage digesters, on the other hand, are of more practical nature.

In general, types of digesters can be divided into two main groups, i.e. those utilizing the dispersed-growth bacteria and those utilizing the attached-growth bacteria. Because most digesters are operated as flow-through without sludge recycle, the dispersed bacteria overflow in the digester slurry, making the HRT equal to the mean cell residence time (θ_c) in the digester. To provide longer θ_c in the digesters, attached-growth bacteria have been employed in which the anaerobic bacteria, attached to artificial media or settled as blanket in the digesters, decompose the organic wastes. Descriptions of the dispersed-growth digesters and attached-growth digesters are given below.

Dispersed-growth digesters

Combined digester and gas holder - fixed dome (Chinese design)

In this type of digester (Figure 4.5) the gas storage volume is directly above the digesting contents of the reactor. The volume of the digester equals the volume of slurry and gas combined. The small-capacity digesters of this type (6-12 m^3) are suitable for single family or a group of families. The larger sizes (50 m^3) are designed for community gas requirements. The roof, walls and bottom of the reactors are constructed either of bricks (in-situ) or precast concrete. The inlet opening and displacement tank are of lime clay. Both the top and the bottom are hemispherical, and are joined together by straight sides. If the digester is constructed from bricks the inside surface is sealed by many thin layers of mortar to make it water and gas tight.

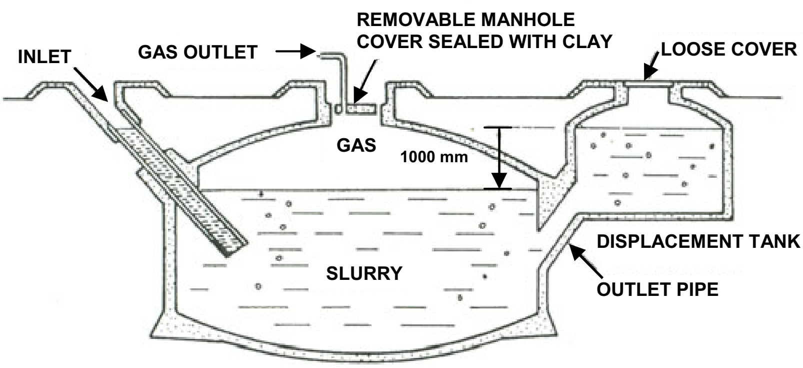


Figure 4.5 Fixed-dome digester

This digester is totally buried underground to ensure uniform temperature distribution, to save space, and to make use of soil support. The inlet pipe is straight and ends at mid level in the digester. The outlet is also at the same level, and consists of a fairly large storage tank. A manhole is provided at the top to gain access to digester during cleaning times. When digester is in operation, this manhole is covered and sealed with clay.

The gas produced during digestion is stored under the dome and displaces some of the digester contents into the effluent chamber; this condition creates gas pressure in the dome of between 1 and 1.5 m of water. The high pressure exerted on the construction is partially balanced by the weight of soil which covers the digester's top.

This type of digester is common in developing countries. Approximately seven millions of this type is in use in China. Most of the operational parameters of this digester are semi-continuous, although some digesters are operated as batch operation. Figure 4.6 shows fixed-dome digesters in a rural village in Thailand.

Figure 4.6 Fixed-dome digesters treating piggery wastewater, central Thailand

Typical feed to these digesters is usually a mixture of animal manure, nightsoil, water hyacinth and agricultural residues, depending on their availability and C/N ratios. The rate of gas production is reported to be 0.15 - 0.2m^3/day per m^3 of digester capacity, but in tropical areas it can be as much as 0.3-0.4m^3/day per m^3 of digester capacity.

Mixing of the digester contents is accomplished through feeding of the influent materials and withdrawal of effluent slurry. An improvement on mixing efficiency of the digester contents is shown in Figure 4.7. In this digester design, mixing is accomplished by pulling the plastic rope back and forth at the inlet and outlet, causing the plastic blades to agitate the slurry to provide better contact between the organic matter and the anaerobic bacteria. This method of mixing prevents both blocking of the inlet and outlet pipes and accumulation of the digested residues in the digestion chamber.

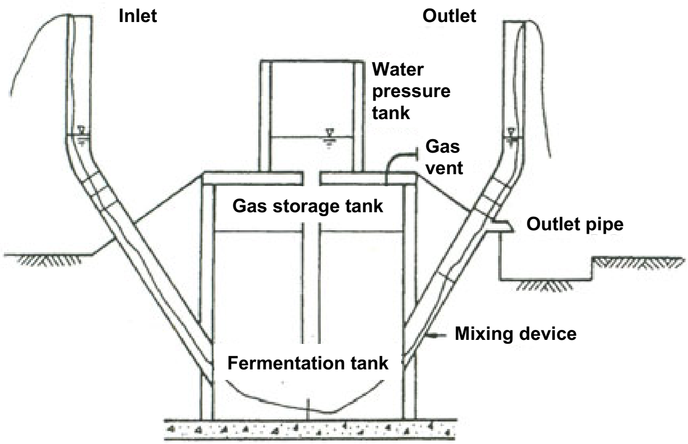


Figure 4.7 Low-cost biogas digester (note a unique mixing device)

Table 4.6 Characteristics of raw materials used to prepare influent mixing

Material	Total organic carbon (%)	Total Kjeldahl nitrogen (%)	Total phos-phorus (%)	Total volatile solids (%)	Carbon/ nitrogen ratio	Moisture content (%)
Nightsoil	47.6	4.5	0.7	85.6	10.7	82.3
Rice straw	42.7	0.9	0.1	77.3	50.3	14.1
Water hyacinth	37.8	1.4	0.4	68.0	27.0	43.7

Table 4.7 Proportions of raw materials used to obtain the desired C/N ratio of 25, and characteristics of influent mixture

Hydraulic retention time (days)	Carbon to nitrogen ratio (C/N ratio)	Total solids to water ratio	Approximate proportion of raw materials (nightsoil/ rice straw/ water hyacinth)		Influent mixture				
			Dry weight basis	Wet weight basis	Total solids (g/L)	Total volatile solids (g/L)	Chemical oxygen demand (g/L)	Total Kjeldahl nitrogen (mg/L)	pH
30	25	8: 92	1.0 : 5.6: 3.0	3.1: 3.2: 4.3	46.9	36.1	46	890	7.4
			-	-					
			1.0: 8.0: 8.0	3.0: 9.5: 11.5					
50	25	8: 92	1.0: 3.4: 1.0	5.5: 3.8: 1.3	49.0	37.7	48.7	900	7.4
			-	-					
			1.0: 0.9: 1.0	8.3: 1.4: 2.1					
70	25	8: 92	1.0: 2.0: 1.0	6.1: 2.2: 1.3	48.1	37.2	49.6	880	7.4
			-	-					
			1.0: 2.8: 1.0	5.6: 3.1: 1.3					

In a study conducted at the Asian Institute of Technology (AIT), Bangkok, Thailand, four pilot small-scale digesters (size = 3.5 m^3) were fed with heterogenous substrate comprising of nightsoil, chopped and sun-dried water hyacinth and rice straw (Polprasert *et al.* 1982). These digesters were operated under ambient conditions (mean temperature = 30°C). The characteristics of these feeding materials are given in Table 4.6; the proportions of these materials mixed to obtain the desired C/N ratio of 25 are shown in Table 4.7. Among the three hydraulic retention times (HRT) studied, biogas production was highest from the digesters operated at an HRT of 30 days (Figure 4.8). A comparison using volumetric methane production rate per unit volume of digester (Table 4.8) showed the digesters operated at the 30-day HRT to give the highest value of 0.33 $m^3/(m^3\text{-day})$; this parameter is important for operational design because it relates the size (or capital cost) of digester to gas production.

Polprasert *et al.* (1982) reported that there was floating scum formed in the digesters fed with a mixture of nightsoil, water hyacinth and rice straw, causing operational problems with mixing and feeding/withdrawal of slurry. Table 4.9 shows the characteristics of the digested slurry which still contained high concentrations of organic matters (based on total volatile solids and chemical oxygen demand) and nitrogen, and thus need to be treated further prior to disposal. On the other hand, this slurry is suitable to be reused as fertilizer or soil conditioner (Figure 4.1).

Table 4.8 Summary of biogas production from the pilot-scale digesters

Hydraulic retention time (days)	Organic loading rates (kg TVS/m^3-day)	Number of digesters	Total biogas production rate (m^3/kg TVS-day)	Volumetric biogas production rate (m^3/m^3-day)	Methane production rate (m^3/kg TVS-day)	Volumetric methane production rate (m^3/m^3-day)
30	1.20	4	0.28	0.33	0.18	0.22
50	0.75	4	0.32	0.24	0.21	0.16
70	0.53	3	0.25	0.13	0.16	0.09

Table 4.9 Characteristics of effluents from biogas digesters

HRT	Number	TS	Reduction	TVS	Reduction	Nonfiltered COD		TKN	Reduction	
(days)	of digesters	g/L	(%)	g/L	(%)	g/L	(%)	mg/L	(%)	pH
30	4	24.7	47	19.1	47.3	24.8	46.7	707.5	20.5	7.4
50	4	18.4	62	13.7	62.7	17.7	63.4	635.8	29.1	7.3
70	3	16.5	68	11.2	70.0	14.9	69.3	619.5	31.4	7.2

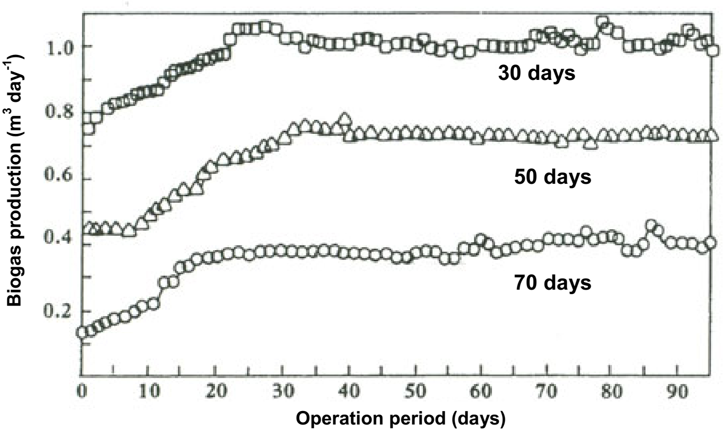


Figure 4.8 Mean daily biogas production at hydraulic retention times of 30, 50, and 70 days from pilot small-scale digesters. Each point is the mean of four digesters.

Floating gas holder digester (Indian design)

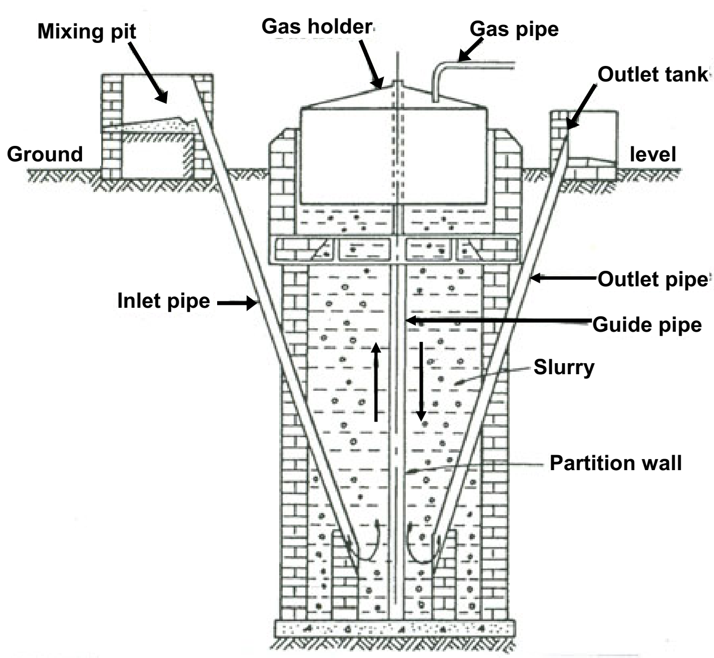
This type of digester, designed by the Khadi and Village Industries Commission (KVIC), India, consists of a cylindrical well, most commonly made from bricks, although chicken wire mesh reinforced concrete has been used. Pressure in the digester remains constant because the gas produced is trapped under a floating cover on the surface of the digester which rises and falls on a central guide (Figure 4.9 a & b). The cover is usually constructed of mild steel, although, due to corrosion problems, other materials such as ferrocement, bamboocement, different kinds of plastic and fiberglass have been used. A major cause for the loss of heat from this kind of digester is its cover. The digester may be buried under the ground to prevent heat loss, leaving the gas holder more or less above the ground

This digester is fed semi-continuously through a straight inlet pipe, and displaces an equal amount of slurry through an outlet pipe. When ratios of height to diameter are high, a central partition wall is built inside the digester to prevent short circuiting of the substrate.

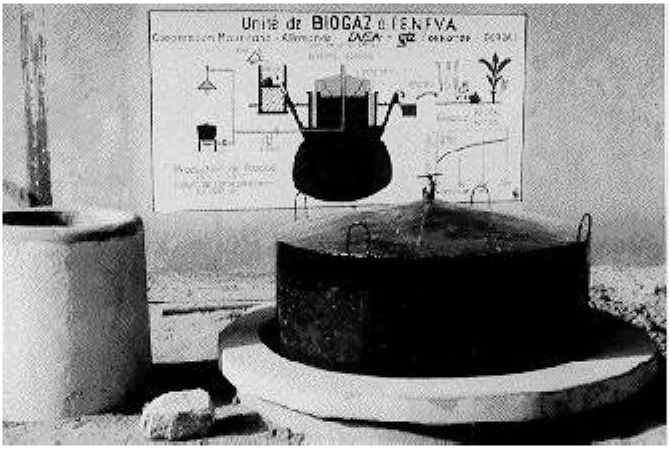
This design is extensively used in India and fed with cattle dung only. If agricultural residues are being used or mixed with animal wastes, the residues should be chopped to small pieces to prevent blockage. This design is simple to build and maintain, and does not require an experienced builder. It is used throughout the world and both it and the Chinese-type fixed-dome digesters are the most common types of digester used for treating organic wastes.

Table 4.10 briefly compares the various aspects of the Chinese and Indian-type biogas digester systems.

Plug-flow digester (Horizontal displacement digesters)
This type of digester consists of a long trench cut into the ground and lined either with concrete or an impermeable membrane. The digester is covered with either a flexible cover anchored to the ground which acts as a gas holder, or with a concrete or galvanized iron top. In the latter type a gas storage tank is required. The main difficulty in plug-flow digestion is to ensure true plug-flow conditions, and to achieve this, the length has to be considerably greater than the width and depth (Figure 4.10). The digester is fed semi-continuously through the inlet which locates at one end of the digester. This type of digester has limited use in developing countries and only a few of them are operating in Mexico. It can sustain relatively high loading rates of organic matter with less frequent failure due to shock loads.



(a)



(b)

Figure 4.9 (a) Schematic of floating gas holder digester. (b) A floating gas holder digester (GATE 2006)

Table 4.10 Comparison between Chinese and Indian designs of biogas digesters (Tam and Thanh 1982)

	Chinese design	Indian design
Construction material	Several different materials	Masonry
	Usually locally available	May be brought from outside village
Construction	Closed, underground masonry or concrete pit with adjacent inlet and outlet	Simply above-ground tank
	Requires skill to build dome, careful lining to prevent gas leaks	Easy to build but hard to install when drum cannot be made or easily carried
	Usually self-help	Self-help possible, but gas holder has to be produced in workshop
Gas storage	In dome combined with digestion chamber	In floating metal drum
	Manometer indicates gas volume	Height of drum indicates gas volume
	For use throughout digester lifespan with occasional linings	Drum needs regular painting to prevent corrosion
	Keeping it gastight is a problem; needs efficient lining	No problem in keeping gastight

Gas pressure	High: up to 1000 mm water column	Low: 70-150 mm water column
	Varying according to gas use	Steady, due to floating drum
	Automatic release of excessive gas through manometer	Automatic release of excessive gas through drum
Efficiency	Low, due to gas escape through large inlets and outlets: 0.15-0.30 m^3 gas produced per m^3 digester per day	Higher, gas escape insignificant: 0.30-0.60 m^3 gas produced per m^3 digester per day
	Stable through seasons, due to good insulation of underground construction	Subjected to seasonal variations, loss heat through metal drum
Feeding materials	Mostly mixtures of animal wastes, human excreta, household refuse, agricultural residues	Virtually semi-continuous loading
Operation	Mostly semi-continuous loading, can be batch operation	Virtually semi-continuous loading
	Effluent removal by pump or bucket	Effluent removal by gravity flow
	Labor-intensive for batch loading, emptying pit and removing effluent	Virtually no attention beyond mix and feeding influent
Maintenance cost	Wall lining	Drum painting
	Low, because no metal part	High due to metal drum

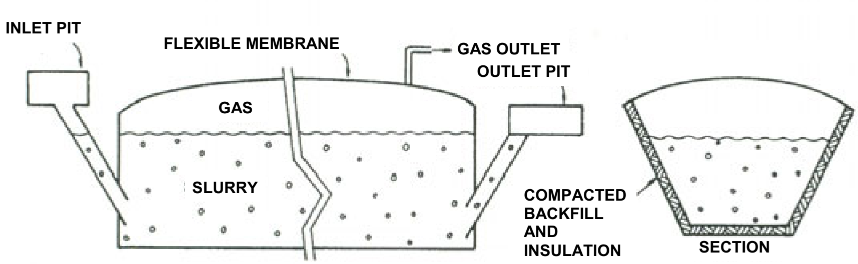


Figure 4.10 Plug-flow digester

Similar to the plug-flow digester is the 'bag digester' which is commonly used in Taiwan and Korea. The early digesters of this type were made of neoprene coated nylon, which was expensive. The present ones are made from red mud plastic (RMP) which is residue of aluminum refineries. There are bag digesters made of PVC in Central America. This is a very light weight digester, easy to install and durable (estimated at 20 years). The Chinese have also started producing this kind of digester. A rapid expansion in the use of bag digesters is expected in China, due to its simplicity, durability, and low cost - US$8/$m^3$ of digester volume (Figure 4.11). This digester is fed semi-continuously. The inlet and outlet to the digester are at opposite ends. The biogas is accumulated at the top of the digester and collected through the gas pipes. The digester is easily installed by excavating a shallow trench slightly deeper than the radius of the digester. This digester is designed to receive mostly swine manure, but other agricultural residues can be added. The reported values of gas production is very much temperature dependent. For swine manure these values are 0.14 m^3/day per m^3 of digester capacity at 8°C to 0.7 m^3 /day per m^3 of digester capacity at 32°C (Hao 1981). A higher gas production rate of 1.53m^3/day per m^3 of digester volume was reported by Yang and Nagano (1985) for the RMP digester operating with slurry recycle at the ratio of 0.25 of the influent flow rate. Anaerobic lagoons covered with plastic sheets can be considered as plug flow digesters. Biogas is stored in the plastic sheets and pumped to the heating facilities. Besides energy recovery through biogas production, covered anaerobic lagoons help to minimize the release of green house gases, such as CH_4 and CO_2, to the atmosphere.

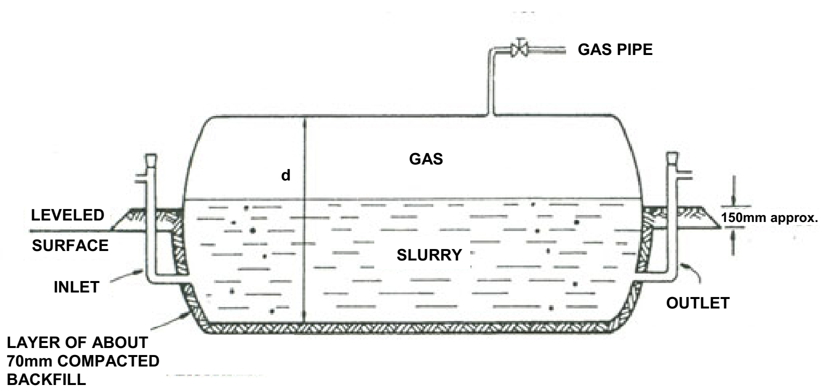


Figure 4.11 Bag digester

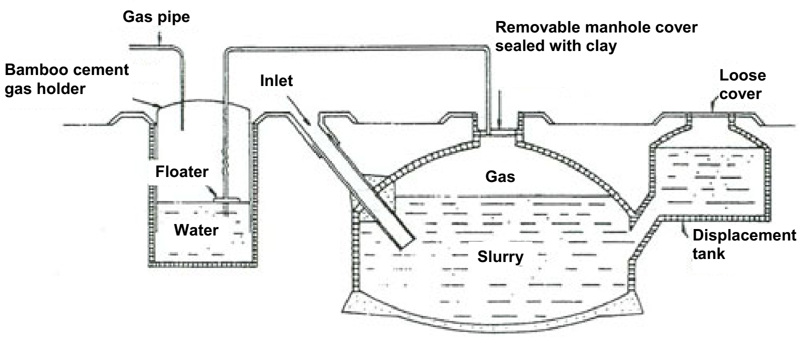


Figure 4.12 Fixed-dome digester with separate gas holder

Separate gas holder digester

This kind of system could be any of the digesters so far explained. The difference is that a separate tank is added for the purpose of gas collection (Figure 4.12). In addition, the gas holding tank can be used as a common reservoir for a few digesters and therefore the system as a whole can serve larger communities or industrial plants. The chief advantage of this kind of system is that it provides a continuous supply of biogas (even in the case of batch system), furthermore, the gas pressure can be regulated and therefore, appliances and engines may be designed and used at their optimum working conditions.

Table 4.11 Design criteria and performance data of dispersed growth biogas digesters

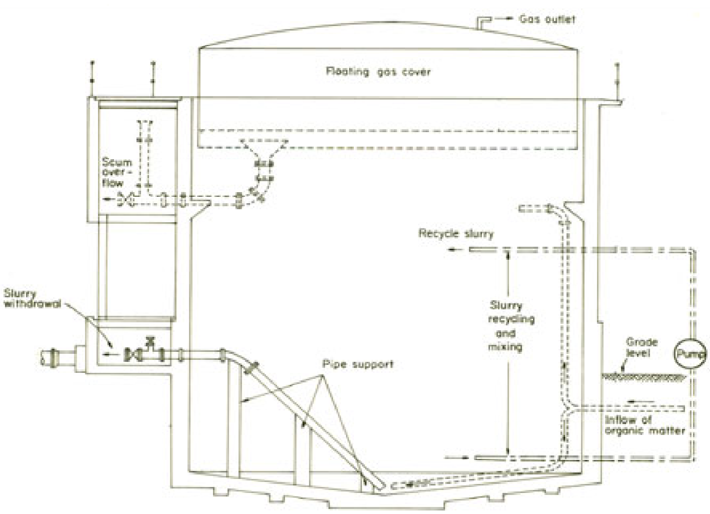
Temperature inside digester (°C)	25-40 (optimum 35, mesophilic)
pH	6.6-7.6 (optimum 7.0-7.2)
Alkalinity (mg $CaCO_3$/L)	2500-5000
C/N ratio	25-30
Loading rate	
(kg VS/m^3-day)	1-4
(kg COD/m^3-day)	1-6
Feed solid content (%)	5-10
HRT (days)	10-60 (no sludge recycle)
Gas production (m^3/day per m^3 of digester capacity)	
Fixed-dome digester	0.15-0.40 (part of digester for gas storage)
Floating gas holder digester	0.30-0.60
Volume for gas storage (% of 1-day gas production)	50-100
Seeding material at start-up	>50% of influent feed

Table 4.11 Design criteria and performance data of dispersed growth biogas digesters (Continued)

Air tightness	Essential
Water tightness	Strongly required
COD removal (%)	30-70
VS removal (%)	40-70
N reduction (%)	20-35

Conventional digesters

This type of digester is used in conventional sewage treatment plants to treat sludge. The gas produced is used to augment the energy demand of the treatment plant or to heat the digester. Figure 4.13 shows a typical design of cylindrical shape digester. Major components of the digester are for mixing and recirculation of the digester contents, elimination of scum, gas collection and digested sludge withdrawal. The operation of the above digesters requires skilled labor and regular monitoring. Variation of designs is in shape and in mixing method. Elimination of scum is easier in a dome-shaped digester because of the low surface area at the top portion of the digester, even though its construction requires special techniques. The size of these conventional digesters ranges from 250 m^3 to 12,000 m^3 or more.



(a)

(b)

Figure 4.13 (a) Schematic diagram of anaerobic digester at Huay Kwang, Bangkok, Thailand. (b) Anaerobic digester at Nongkham, Bangkok, Thailand.

Besides the above types of digesters, there are numerous modifications of biogas digesters made to suit particular needs and local conditions. Schematic drawings of these modifications can be found in the book "Biomethanation" by Brown and Tata (1985). A summary of design criteria and performance data of dispersed-growth biogas digesters is given in Table 4.11.

Attached-growth digesters

Anaerobic filter (Young and McCarty 1969)

This is essentially a filter column packed with stationary media such as rocks, gravels or different types of proprietary plastic materials (Figure 4.14). Columns with media having a larger specific surface area (surface area per unit volume of the medium) will have more fixed-film bacteria attached to the media and some entrapped within the void spaces of the media. In general, the packing media to be installed in anaerobic filters should have a high specific surface area (surface area to volume ratio) to provide a large surface for the growth of attached biofilms, while maintaining a sufficient void volume to prevent the reactor from plugging either from particulate solids entering with influent waste stream or bacterial floc growing within the reactor (Vigneswaran *et al.* 1986). Commercial media available for use in anaerobic filters include loose fill media such as Pall rings and modular block media formed from corrugated plastic sheets, in which the channels in modular media may be tubular or crossflow (Figure 4.15). The specific surface area of media used in full scale anaerobic filters averages approximately 100 m^2/m^3. Table 4.12 lists size, specific surface area and porosity of some packing media used for anaerobic filters. The waste flows upward or downward through the anaerobic filter column, contacting the media on which anaerobic bacteria grow and are retained. Because the bacteria are retained on the media and not easily washed off in the effluent, the mean cell residence times (θ_c) on the order of 100 days can be achieved with short HRT (Metcalf and Eddy Inc. 2003). Table 4.13 shows the advantages and disadvantages of anaerobic filter process, while Table 4.14 reports operating and performance data of some full-scale anaerobic filters in U.S.A. and Canada. Depending on the flow regime, the enrichment of the acid- and methane-forming bacteria takes place at different zones in the filter. For an up-flow column, there will be enhancement of the acid formers and methane formers at the bottom and top regions, respectively.

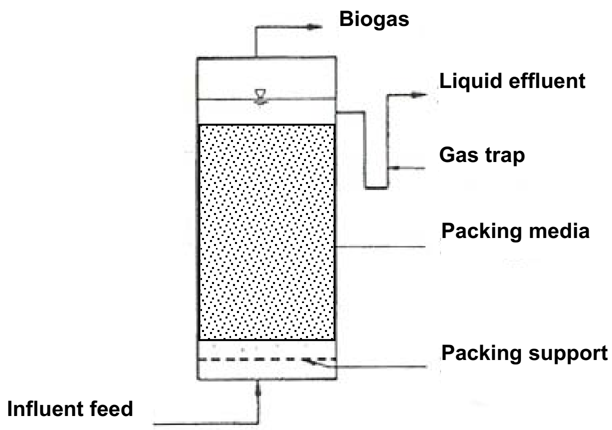


Figure 4.14 Up-flow anaerobic filter

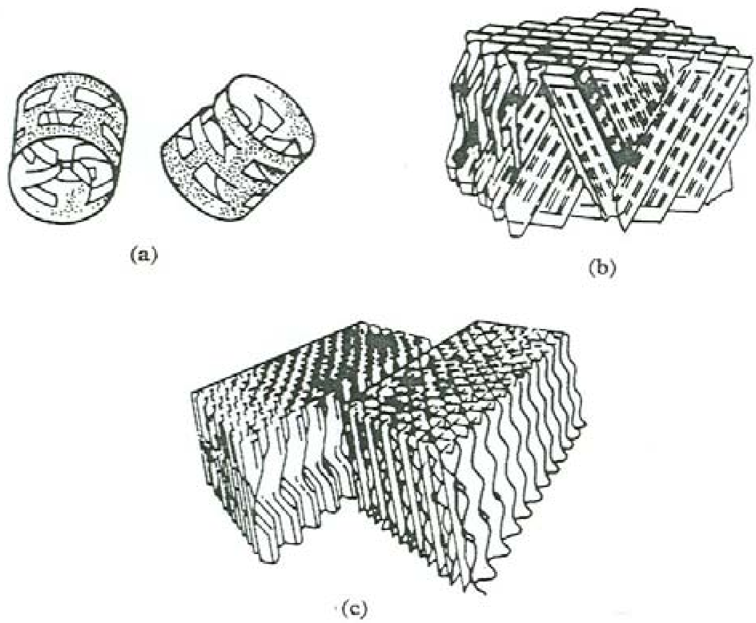


Figure 4.15 Packing media for anaerobic filters: (a) pall ring; (b) crossflow media; (c) tubular media

Table 4.12 Packing media for anaerobic filters (Henze and Harremoes 1983)

Material	Characteristics	Specific surface area (m^2/m^3)	Empty bed porosity
Quartz stone	20-40 mm dia.		0.42
Granite stone	25-38 mm dia.		0.53
Lime stone	20-40 mm dia.		0.49
Gravel	6-38 mm dia.		0.4
Oyster shells	60-100 mm dia.		0.82
Active carbon	1.5 mm dia.		0.60
Red clay blocs	28.28 mm pore size	157	0.7
Corrugated blocs		98-132	0.95
PVC	25 mm dia.		
Granite chips	12-25 mm		0.40
Pall rings	90.90 mm	102	0.95
Norton plastic rings	90 mm	114	0.95
Rachig rings	10.16 mm	45-49	0.76-0.78
Polypropylene spheres	90 mm dia.	89	>0.95

Table 4.13 Characteristics of anaerobic filter process

Advantages	Disadvantages
High organic removal capacity	Difficult to start up
Short HRT	Risk for clogging
Good adaptation to different wastewater	Restricted to wastewater with low TSS
Application to dilute and high strength wastewater	High TSS and NH_4-N contents in the effluent
No mechanical mixing required	May require periodic biomass removal
Intensive against load fluctuations	Limited access to reactor interior for monitoring and inspection of biomass accumulation
Low area demand	High costs for packing media and support systems

Because of the physical configuration of the filter, only soluble waste or wastes with low solid contents including domestic wastewater should be treated to avoid frequent clogging of the filter.

Up-flow anaerobic sludge blanket (UASB) reactor

This type of reactor, developed by Lettinga *et al.* (1983) in the Netherlands, is suitable for the treatment of high-strength organic waste that is low in solid content (e.g. the agro-industrial wastes mentioned in Chapter 2) with or without sludge recycle. The digester has three distinct zones: a) a densely packed sludge layer at the bottom, b) a sludge blanket at the middle, and c) a liquid layer at the top (Figure 4.16).

Wastewater to be treated enters at the bottom of the reactor and passes upward through the sludge blanket composed of biologically formed granules. Treatment occurs as the wastewater comes in contact with the granules. The gases produced under anaerobic conditions (principally CH_4 and CO_2) cause internal sludge circulation, which helps in the formation and maintenance of the biological granules. Some gas bubbles, produced within the sludge blanket, become attached to the biological granules and bring them to the top of the reactor. The granules that reach the surface hit the bottom of the inverted pan-like gas/solids separator (degassing baffles), which causes the attached gas bubbles to be released. The degassed granules typically settle to the sludge blanket zone, thus creating a long mean cell residence time (θ_c) and a high solid concentration in the system. About 80 - 90 percent of the decomposition of the organic matter takes place in the sludge blanket zone; this occupies about 30 percent of the total volume of the reactor. To keep the sludge blanket in suspension, upflow velocities in the range of 0.6-0.9 m/hr have been used (Metcalf and Eddy Inc. 2003).

Table 4.15 summarizes the advantages and disadvantages of the UASB process, while the design and performance data of some UASB reactors in the U.S. and Netherlands are given in Table 4.16. To minimize the overflow of granules in the effluent, the design guidelines of the gas-solids separator device for UASB reactors, listed in Table 4.17, should be followed.

It should be noted from Table 4.16 that the volumetric gas production rates from the UASB reactors, ranging from 3.7 to 7.5 m^3/m^3 of reactor volume, are over 10 times higher than those of the conventional biogas digesters (see Table 4.8). This is probably due to three reasons: a) the UASB reactors were fed with wastes which contain high concentrations of soluble COD and are readily biodegradable; b) better mixing and less shorting-circuiting in the UASB reactors; and c) due to the internal sludge circulation in the UASB reactors, more active microorganisms in the form of granules are available for anaerobic biodegradation. However, it is much more expensive to build a UASB reactor than a conventional biogas digester.

Besides the anaerobic filter and UASB reactor, other anaerobic fixed-film reactors have been developed such as the fluidized and expanded bed reactors. Since the fixed-film bacteria stay in the reactor longer or have longer θ_c than the dispersed bacteria, they are able to withstand shockloading or receive higher organic loadings better than the dispersed bacteria. Application of anaerobic fixed-film reactors in waste treatment and biogas production is current growing.

Table 4.14 Operating and performance data of some full-scale anaerobic in the U.S.A. and Canada (adapted from Young and Yang 1991)

Type of waste (major constituent)	Feed COD or BOD (mg/L)	COD loading (kg/m^3- day)	Temp. (°C)	HRT	Percent removal	Reactor data
Wheat starch (Carbohydrates)	8,000 COD 6,500 BOD	4.4	32	44 hr	70-80 COD	Upflow, V = 760 m^3, D = 9 m, H = 6 m, M = 12-50 stone
Chemical processing (alcohols)	12,000 COD	8-12	37	24-36 hr	75-85 COD	Upflow, V = 6,400 m^3, D = 26 m, H = 12.2 m, M = 90 mm pall ring
Rum distillery (carbohydrate)	85,000 COD 40,000 BOD	6-7	38	12-14 days	65-75 COD 70-80 BOD	Downflow, V = 12,500 m^3, D = 36 m, H = 12 m, M = tubular modules
Landfill leachate (organic acids)	11,000 COD 8,650 BOD	0.2-0.7	37	30-40 days	90-96 BOD	Upflow, V = 2,800 m^3, D = 18.3 m, H = 11 m, M = tubular modules
Food canning (carbohydrate)	4,000 COD 2,500 BOD	1.2-2.5	35	48-72 hr	89 COD 97 BOD	Upflow, V = 3,600 m^3, D = 33 m, H = 4 + m, M = crossflow modules

[a] V = reactor volume, D = reactor diameter, H = reactor height, M = media

Table 4.15 Characteristics of the UASB process (adapted from Weiland and Rozzi 1991)

Advantages	Disadvantages
High organic removal capacity	Granulation process difficult to control
Short HRT	Granulation depends on wastewater properties
Low energy demand	Start-up eventually needs granular sludge
No need of packing media	Sensitive to organic and hydraulic shock loads
Long experience in practice	Restricted to nearly solid free wastewater
	Ca^{2+} and NH_4^+ inhibit granular formation
	Re-start can result in granular flotation

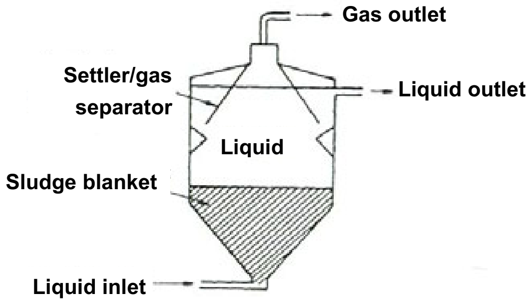


Figure 4.16 Upflow anaerobic sludge blanket digester

4.4.3 Trouble-shooting

All biogas digesters will have problems sooner or later with their structure components and in the operation and maintenance. Tables 4.18 and 4.19 deal with problems associated with the dispersed-growth digesters, their causes and remedies; while Table 4.20 deals with those of the attached-growth digesters, i.e. anaerobic filters and UASB.

Table 4.16 Design and performance data of UASB reactors in the U.S. and Netherlands (adapted from Biljetina 1987)

Reactor description			Operating data				Gas production	
Type of waste	Location	Capacity	HRT (hr)	Feed COD (mg/L)	COD loading (kg/m^3-day)	COD removal (%)	Gas prod. (m^3/h)	% CH_4
Brewery	LaCrosse, Wisc	961.4 m^3/hr	4.9	2,500	16.34	80	35,300	75
Potato starch	Caribou, Maine	37.85 m^3/hr	47	22,000	11.05	85	7,800	77
Alcohol	ZNSF, Nether.	10977 kg COD/day	8	5,330	16.02	90	NA[a]	NA[a]
Sugar beet	CSM Breda, Nether.	15568 kg COD/day	4.8	2,400	12.02	75	200	82

[a] NA = not available

Table 4.17 Guidelines for the design of the gas-solids separator device for UASB reactor (Lettinga and Hulshoff Pol 1992)

1. The slope of the settler bottom, i.e., the inclined wall of the gas collector, should be between 45-60°.
2. The surface area of the apertures between the gas collectors should not be smaller than 15-20% of the total reactor surface area.
3. The height of the gas collector should be between 1.5-2 m at reactor heights of 5-7 m.
4. A liquid gas interface should be maintained in the gas collector in order to facilitate the release and collection of gas bubbles and to combat scum layer formation.
5. The overlap of the baffles installed beneath the apertures should be 10-20 cm in order to avoid upward flowing gas bubbles entering the settler compartment.
6. Generally scum layer baffles should be installed in front of the effluent weirs.
7. The diameter of the gas exhaust pipes should be sufficient to guarantee the easy removal of the biogas from the gas collection cap, particularly also in the case where foaming occurs.
8. In the upper part of the gas cap anti-form spray nozzles should be installed in the case where the treatment of the wastewater is accompanied by heavy foaming.

4.5 BIOGAS PRODUCTION

Rate of biogas yield per unit weight of organic wastes can vary widely depending on the characteristics of influent feed and environmental conditions in the digesters as stated in section 4.3. Data of biogas production from various types of wastes can be obtained from literature or can be theoretically estimated from chemical stoichiometry and kinetic reactions. This information is given below.

A compilation of data of biogas yield from various organic waste materials is presented in Table 4.21. The range of biogas production is 0.20-1.11 m^3/kg of dry solids, with CH_4 content being 57-69%. Theoretically, CH_4 production can be determined according to the method outlined in Metcalf and Eddy Inc. (2003):

During anaerobic digestion biodegradable organic matter (BOD_L) is covered to mainly:

- CH_4, CO_2, NH_3, H_2 and trace quantities of other gases, and
- Biological cells.

Table 4.18 Problems with the digester, gas holder, and pipes (adapted from Tata Energy Research Institute 1982)

	Problem	Possible cause	Remedy
Digester	1. Cracking of the digester wall due to hydraulic pressure from inside or from outside in horizontal gas plants.	Lack of consolidation of soil on the outside of the digester wall, resulting in cavities in soil surrounding the masonry wall, and leading to the development of cracks in the digester wall.	Outlet part of the plant should be packed in layers of soil of 30 cm thickness each, with sufficient water, after the construction of the digester is completed. This would increase the life of the structure and also reduce seepage loss to some extent.
	2. Rising of the digester floor with the rise of ground water table.	a) Faulty compaction of the bottom. b) Hydraulic pressure of ground water.	Pressure is neutralized when the plant is full. So where the water table is high the plant should always remain full.
	3. Bursting of the digester with excessive gas pressure.	a) Gas holder at the top becomes jammed in the digester due to drying of the scum in between the gas holder and digester and restricting movement of the holder.	a) Scum should not be allowed to dry and should be forced down with a rod 2-3 times a week.
		b) Guide frame gets loosened from its support and the holder cannot move freely.	b) Guide pipe should be rewelded and rivetted and guideframe, etc., should be checked before installing it in the digester.

Table 4.18 Problems with the digester, gas holder, and pipes (adapted from Tata Energy Research Institute 1982) (continued)

	Problem	Possible cause	Remedy
Gas holder	1. Corrosion of the gas holder.	Gas holders, commonly made of mild steel, remain in contact with digester slurry and with the gas containing methane and other gases, including H_2S which is highly corrosive.	Painting of the gas holder with black paint or even coal tar each year. Alternate materials like PVC, ferrocement, galvanized iron, fiberglass, etc. may be used for manufacturing the holder.
Inlet and outlet and central guide pipes	1. Clogging of the inlet/outlet pipes.	1. Accumulation of feed or scum.	1. Should be washed or flushed regularly with clean water or should be cleaned with a pole moving up and down.
	2. Breakdown of central guide pipe.	2. Rusting	2. Replacement (as it is mostly beyond repair).
Gas pipe carrying gas to the utilities	1. Collection of condensate.	Presence of water vapors in the gas.	Condensate should be blown out 2-3 times a week. The pipe may be kept at a slope to ease blowing off.

Table 4.19 Problems with the operation of the biogas plant (adapted from Tata Energy Research Institute 1982)

Problem	Cause	Remedy
1. Gas holder (of floating type) does not rise or bag (of flexible bag type) does not inflate or pressure (of fixed dome type) does not rise at the start of the operation.	a) Very few bacteria	a) Seed with slurry from a working digester before adding the new slurry to the digester; rotate the gas holder daily.
	b) Lack of acclimation time.	b) In cold weather it takes about 3 weeks to fill the gas holder for the first time.
	c) Feeding of slurry while waiting for gas holder to fill.	c) No slurry should be fed in until sufficient amount of burnable gas has been produced.
	d) No water in water outlet device.	d) About 0.25 L of water should be poured into the dipper pipe and the excess removed.
	e) Leak in gas holder or gas pipe.	e) Should be located and repaired.
2. Gas holder or bag (or pressure in fixed dome type plant) goes down very quickly once main gas valve is opened.	a) Condensate or water outlet tap open (if fitted) or gas tap for burner open or gas cock for lamp open.	a) Close the taps.
	b) No water in water outlet device or syphon.	b) Pour water into water outlet device to remove excess water.
	c) Major leak in the pipe-work.	c) Leaks should be located and repaired

Table 4.19 Problems with the operation of the biogas plant (adapted from Tata Energy Research Institute 1982) (continued)

Problem	Cause	Remedy
3. Gas holder or bag or pressure (in fixed dome digester) rises very slowly.	a) Temperature too low.	a) Temperature may be raised by, e.g., solar heating, heating with biogas, and composting around the digester wall.
	b) Thick scum on top of slurry.	b) Remove the scum layer by agitating the drum daily and seeing to it that no straw or grass, etc. get into the plant.
	c) Too much slurry put in daily.	c) Correct amount of slurry should be added daily.
	d) Slurry mixture suddenly changed a lot.	d) Slurry mixture should not be altered too much at a time.
	e) Chemicals, oil, soap or detergent put into slurry.	e) Daily feed with dung and water only, to be continued.
	f) Gas leak.	f) Leak should be located and repaired.
	g) Slurry mixture too thick or too thin.	g) Slurry to be made of the right consistency.
4. Too little gas although pressure is correct.	Gas jet is blocked.	Gas jet to be cleaned with split bamboo or needle.

Table 4.19 Problems with the operation of the biogas plant (adapted from Tata Energy Research Institute 1982) (continued)

Problem	Cause	Remedy
5. No gas at the burner.	a) Main valve is closed.	a) Open the valve.
	b) Gas tap is blocked.	b) Clean the tap.
	c) Burner or pipe is completely blocked by condensate.	c) Remove the condensate.
6. First gas produced will not burn.	a) Wrong kind of gas.	a) First gas should not be burned as air may be mixed with it and could explode. Also, frequently the first gas produced in winter has a high percentage of CO_2.
	b) Air in the gas pipe.	b) Air should be allowed to escape until there is a definite smell of gas.
7. Formation of scum.	a) Presence of undigested vegetable matter (e.g. straw, water hyacinth or coarse dung such as elephant dung), animal bedding (e.g. straw, sawdust), animal clothing (e.g. pig hair, chicken feathers) and not properly broken dung.	
	b) Slurry not properly mixed.	
	c) Mixing the slurry to disperse the floating material.	

Table 4.19 Problems with the operation of the biogas plant (adapted from Tata Energy Research Institute 1982) (continued)

Problem	Cause	Remedy
8. pH too acidic (pH < 6)	a) Adding raw material too fast.	a) Reduce feeding rate.
	b) Wide temperature fluctuation.	b) Stabilize temperature.
	c) Build-up of scum.	c) Remove scum.
9. pH too alkaline (pH > 7)	Initial raw material too alkaline.	Have patience. Never put acid into the digester.
10. Slow rate of gas production or no gas production.	a) Increase in toxicity with retention time.	a) Dilution or low loading makes ammonia toxicity less critical.
	b) Increase in solid content.	b) Stirring, dilution or low loading reduces viscosity.
	c) pH too acidic or too alkaline.	c) As discussed earlier in Problems 8 and 9.
	d) Low temperature.	d) Raise the temperature by heating.
	e) Addition of significant quantity of different types of feed material to a working digester, for example, addition of an equal mass of vegetable matter to the digester utilizing pig waste.	e) Do not change the slurry mixture of a working digester.

Table 4.20 Problems with anaerobic filters and UASB reactors (Lettings *et al.* 1983; Vigneswaran *et al.* 1986; Henze and Harremoes 1983)

	Problem	Cause	Remedy
Anaerobic filter	Start-up difficulty	Improper seeding or improper initial loading	Inoculation with the right microbial culture.
			Low initial loading during start-up (approx. 0.1 kg COD/kg VSS/day)
	Channelling and short circuiting	Gas bubbles adhere to flocs/bed particles and cause these to rise in the reactor	Backwashing to remove excess solid build-up in the voids
	High levels of SS in reactor effluent	Clogging due to too much solids retained in the filter	Remove the solids from packing by draining and backwashing the media
UASB	Start-up difficulty	Improper seeding or improper initial sludge loading	Amount of seed sludge: 10-15 kg VSS/m^3. Initial organic load: 0.05-0.1 kg COD/kg VSS/day. No increase of the organic load unless all VFA's are more than 80% degraded. Permit the wash-out of poorly settling sludge. Retain the heavy part of sludge.
	Buoying sludge pushed through the aperture and overflow with the liquid effluent	Ineffective separation of the entrapped or attached gas from the sludge flocs at the gas-liquid interface	Keep the gas-liquid interface well stirred to allow entrapped gas to readily escape.

Table 4.21 Yield of biogas from various waste materials[a]

Raw materials	Biogas production per unit weight of dry solids		Temperature		CH_4 content in gas (%)	Fermentation time (days)
	ft^3/lb	m^3/kg	(°F)	(°C)		
Cow dung	5.3	0.33	-	-	-	-
Cattle manure	5	0.31	-	-	-	-
Cattle manure (India)	3.6-8.0	0.23-0.50	52-88	11.1-31.1	-	-
Cattle manure (Germany)	3.1-4.7	0.20-0.29	60-63	15.5-17.3	-	-
Beef manure	13.7[b]	0.86[b]	95	34.6	58	10
Beef manure	17.7	1.11	95	34.6	57	10
Chicken manure	5.0[c]	0.31[c]	99	37.3	60	30
Poultry manure	7.3-8.6[f]	0.46-0.54[f]	90.5	32.6	58	10-15
Poultry manure	8.9[c]	0.56[c]	123	50.6	69	9
Pig manure[d,e]	11.1-12.2	0.69-0.76	90.5	32.6	58-60	10-15
Pig manure[d,e]	7.9	0.49	91	34.6	61	10

Table 4.21 Yield of biogas from various waste materials[a] (continued)

Raw materials	Biogas production per unit weight of dry solids		Temperature		CH_4 content in gas (%)	Fermentation time (days)
	ft^3/lb	m^3/kg	(°F)	(°C)		
Sheep manure[d]	5.9-9.7	0.37-0.61	-	-	64	20
Forage leaves	8	0.5	-	-	-	29
Sugar beet leaves	8	0.5	-	-	-	14
Algae	5.1	0.32	113-112	45-50	-	11-20
Nightsoil	6	0.38	68-79	20-26.2	-	21

[a] Compiled by NAS (1977)

[b] Based on total solids
[c] Based on volatile solids fed
[d] Includes both feces and urine
[e] Animals on growing and finishing rations
[f] Based on volatile solids destroyed. On the basis of conversion efficiencies, these results may be expressed as 4.0-4.7 ft^3/lb dry solids added or 0.26-0.30 m^3/kg
Note: Some of the reported values are higher than the theoretical value of 0.35 m^3 CH_4/kg COD given in Equation 4.10 and care must be taken in applying these data in practices

Organic matter used for CH_4 production

= Organic matter stabilized - Organic matter used for cell production (4.6)

= (BOD_L stabilized – BOD_L for cell production) (4.7)

A relationship between BOD_L and CH_4 production is considered as follows:

$$C_6H_{12}O_6 \longrightarrow 3\,CH_4 + 3\,CO_2 \tag{4.8}$$

$$3\,CH_4 + 6\,O_2 \longrightarrow 3\,CO_2 + 6\,H_2O \tag{4.9}$$

180 kg glucose produces 48 kg CH_4
180 kg glucose is equivalent to 192 kg BOD_L
i.e. 1 kg BOD_L produces

= (48/180)x(180/192) kg CH_4
= 0.25 kg CH_4
= 0.25 kg x (10^3 mol/16 kg)
x (22.4 L/1 mol) x (1 $m^3/10^3$ L)
= 0.35 m^3 CH_4 at STP (standard temperature & pressure)

Volume of CH_4 produced, m^3/day

= 0.35 (BOD_L stabilized – BOD_L for cell production) (4.10)

To solve Equation 4.10, the terms "BOD_L stabilized" and "BOD_L for cell production" need to be determined.

BOD_L stabilized = $EQS_o\,(10^3\text{ g/kg})^{-1}$ kg/day (4.11)

Where: E = Efficiency of waste stabilization, fraction
Q = Influent flow rate, m^3/day, and
S_o = Ultimate influent BOD, g/m^3

From Equation 2.5,

$$\frac{\text{kg } O_2}{\text{kg Cells}} = \frac{160}{113}$$

in which, $BOD_L = 1.42\ P_x$ (4.12)

Where: P_x = net mass of cells produced

From Monod equation and considering mass balance in a digester without cell recycle, the term "P_x" in kg/day can be expressed as follows:

$$P_x = \frac{QYES_o}{1 + k_d\theta_c} \times 10^{-3} \tag{4.13}$$

Where: Y = yield coefficient of anaerobic bacteria (normally = 0.10), and
k_d = decay coefficient of anaerobic bacteria (normally = 0.02-0.04 day^{-1})
θ_c = mean cell residence time, days

Substituting Equations 4.11, 4.12 and 4.13 into Equation 4.10, the following is obtained:

Volume of CH_4 produced, m^3/day

$$= 0.35\ E\ Q\ S_o\ (10^{-3})\ (1 - (1.42\ Y / (1 + k_d\theta_c))) \tag{4.14}$$

If the kinetic coefficients Y and k_d for cell production and the efficiency of waste stabilization (*E*) in a digester are known, then CH_4 production can be predicted from Equation 4.14. Experimental method to determine values of the kinetic coefficients for a particular type or mixture of influent feed is outlined in Metcalf and Eddy Inc. (2003), or these values can be obtained from literature.

It should be noted that Equation 4.14 is applicable to only dispersed-growth digesters without sludge recycle. Although kinetic models for methane production and waste stabilization for attached-growth digesters have been developed, their application to field-scale digesters is not yet widely adopted.

An example showing the application of Equation 4.14 is given in Example 4.1. Example 4.2 is a simplified method to design a biogas digester using data obtained from the literature.

Example 4.1

A tapioca industry produces wastewater with the characteristics as shown below.

Flow rate = 100 m^3/day
COD = 20,000 mg/L
N = 400 mg/L

Determine the quantity of CH_4 that can be produced from a dispersed-growth digester treating this tapioca wastewater and the digester size. Assume that at the θ_c value of 10 days, there is a waste stabilization efficiency of 65% and the values of Y and k_d were experimentally found to be experimentally found to be 0.05 and 0.02 day^{-1}, respectively.

Solution

From Equation 4.14,

$$CH_4 \text{ produced} = 0.35(0.65)(100)(20{,}000)(10^{-3})\left\{1- \frac{1.42(0.05)}{1+0.02(10)}\right\}$$

$$= 423.1 \text{ m}^3/\text{day}$$

Note: if COD represents total C in the wastewater, the ratio of COD/N = 50/1 which is more than the optimum value of 25/1. This tapioca wastewater needed to add with some nitrogenous compounds (such as urea) to adjust the C/N ratio prior to feeding to the digester.

$$\text{Volume of this digester is} = 100 \text{ m}^3/\text{day x } 10 \text{ days}$$
$$= 1000 \text{ m}^3$$

Construct 2 conventional digesters, each with a working volume of 500 m^3

Example 4.2

A family of five persons needs about 10 m^3 of methane for family uses daily. Determine the size of biogas digester required and other operating procedures necessary to maximize the gas production. Raw materials available are nightsoil and rice straw.

Characteristics of raw materials:

	Nightsoil	*Rice straw*
Organic Carbon (C), % total solids	48	43
Kjeldahl Nitrogen (N), % total solids	4.5	0.9
Volatile Solids (TVS), % total solids	86	77
% Moisture	82	14

Let the dry weights of nightsoil and rice straw required to be fed to the digester be m_1 and m_2 kg/day, respectively. An optimal condition for anaerobic digestion should have a C/N = 25/1 in the influent feed:

$$\frac{0.48\, m_1 + 0.43\, m_2}{0.045\, m_1 + 0.009\, m_2} = 25$$

$$m_2/m_1 = 0.645/0.205 = 3.15 \quad (4.15)$$

From Table 4.21, choose a methane production rate
= 0.3 m^3/kg TVS added.

TVS required/day = 10/0.3 ≈ 33.33 kg, or $0.86\, m_1 + 0.77\, m_2 = 33.33$ (4.16)

From Equations 4.15 and 4.16
m_1 = 10.16 kg/day
m_2 = 32 kg/day

Wet weight of nightsoil required = 10.16/0.18 = 56.44 kg/day
Wet weight of rice straw required = 32/0.86 = 37.22 kg/day

$$\text{Volume of digester} = \frac{\text{Volatile solids added/day}}{\text{Volatile solids loading}}$$

The normal range of volatile solids loading

= 1-4 kg VS/(m^3-day)(Barnett *et al.* 1978)

Choose a volatile solids loading rate = 2 kg VS/(m^3-day)
The volume of digester required = 33.33/2 ≈ 17 m^3
To provide additional space for gas storage, the digester volume should be approximately 22-25 m^3.
The normal hydraulic retention time = 10-60 days (Barnett *et al.* 1978 and section 4.3)
Choose a hydraulic retention time = 30 days
Waste volume to be added/day = 17/30 = 0.57 m^3/day = 570 L/day
Assume bulk densities of 1.1 and 0.1 kg/L for nightsoil and rice straw, respectively.
Volume of raw wastes to be added each day:
= (56.44/1.1) + (37.22/0.1)
= 423.5 L

Volume of dilution water required to be added to the influent mixture:

= 570-423.5
= 146.5 L/day

The design and operation of a biogas digester can follow those outlined in the above example. In practice, the process of digester size selection may be as follows. First, gas plant size is determined. This requires an estimate of the daily requirements of biogas (see Table 4.22), coupled with the availability of the organic materials which is given in Chapter 2. In calculating the required volume for digester, the amount of dilution water needed and additional space for gas storage should be considered.

4.6 END USES OF BIOGAS AND DIGESTED SLURRY

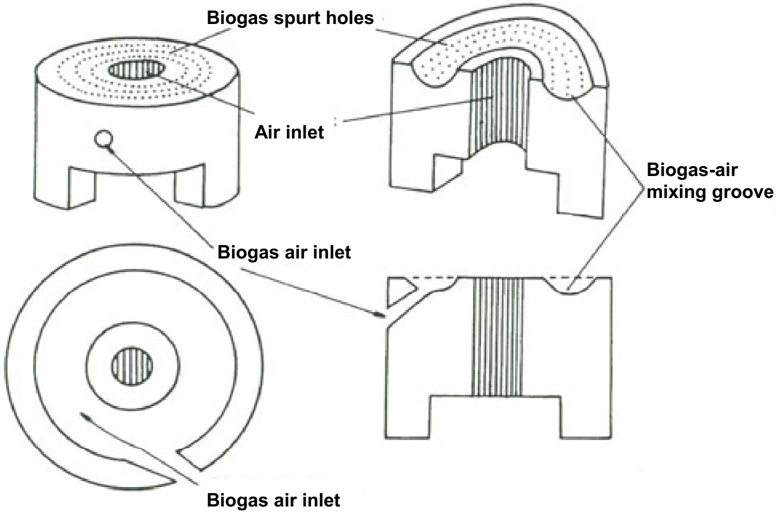
4.6.1 Biogas

Based on the heat value of the biogas (4,500-6,300 k-cal/m^3), Hesse (1982) estimated that on complete combustion one m^3 of biogas is sufficient to:

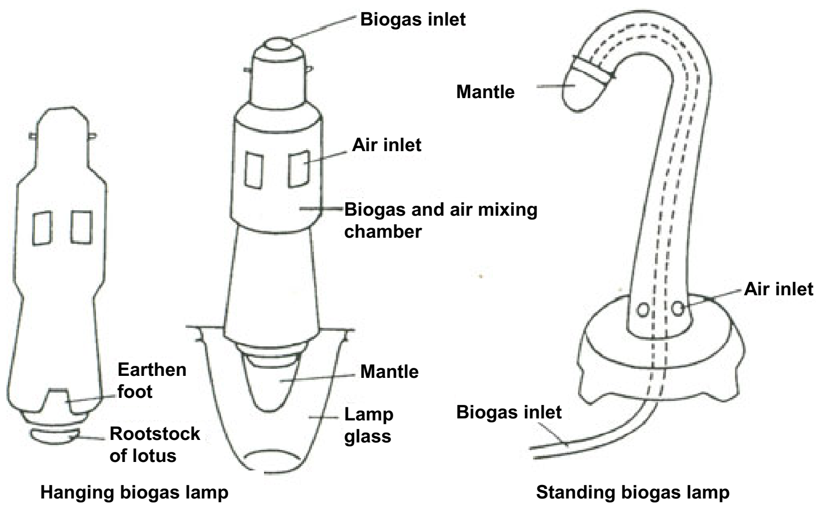
- run a 1 horsepower (hp) engine for 2 hours
- provide 1.25 kWatt-hour of electricity
- provide heat for cooking three meals a day for five people
- provide 6 hours of light equivalent to a 60-Watt bulb
- run a refrigerator of 1-m^3 capacity for 1 hour
- run an incubator of 1-m^3 capacity for 0.5 hour.

Therefore 1 m^3 of biogas is equivalent to 0.4 kg of diesel oil, 0.6 kg petrol or 0.8 kg of coal. Quantities of biogas required for specific application are presented in Table 4.22. Figure 4.17 shows examples of stoves and lamps that use biogas as fuel for their operation.

In China and India a large number of rural households are being served by biogas (Barnett *et al.* 1978). About 95% of all the biogas plants in Asia are of family-size type and therefore the principal uses of their output are cooking and lighting. The remaining 5% of biogas plants are being used for other purposes like refrigeration, electricity generation, and running irrigation pumps. For these purposes it becomes necessary to compress and store the gas in containers made of a variety of materials such as PVC, rubber and polyethylene which are commercially available as shown in Figure 4.18.



a) Earthen stove with mixing groove



b) Biogas lamps

Figure 4.17 (a) Biogas stove and (b) lamp (after McGarry and Stainforth 1978; reproduced by permission of the International Development Research Centre, Canada

Engines are designed to run either on pure methane gas or digester gas. Either type of gas is a suitable fuel for petrol and diesel engines. Diesel engines to run on dual fuel (biogas/diesel oil) or diesel fuel only are now manufactured in India. Kerosene- and gas-operated engines can also be modified to use biogas. Stationary engines located near a large-size biogas plant can be an economical and practical proposition. It is more efficient to use biogas to generate electricity rather than direct lighting. However, high cost of engine and generator might be prohibitive for the farmers or biogas owner. Figure 4.19 is a co -generator run on biogas produced from digestion of solid wastes. The produced electricity is used in the plant and also sold to the electricity authority, while the produced heat is used to dry the digested sludge to make it suitable for land application.

The biogas from digestion of animal manure and vegetable matter normally do not contain sufficient quantity of H_2S to require purification before use. For cooking and lighting, the biogas does not need to be purified. However, if the gas is to be stored or transported, then H_2S should be removed to prevent corrosion of storage bags. CO_2 should also be removed as there is no advantage in compressing it. Biogas purification is not normally practiced for small-scale digesters. For large-scale or institutional digesters, there might be economic reasons favoring biogas purification. Some practical methods of biogas purification are described below.

CO_2 removal

Since CO_2 is fairly soluble in water, water scrubbing is perhaps the simplest method of CO_2 removal from biogas. However, this method requires a large quantity of water for scrubbing CO_2, as can be estimated from Table 4.23. Assuming that a biogas has 35 % CO_2 content and CO_2 density is 1.84 kg/m^3 at 1 atmospheric pressure and at 20 °C, the amount of water required is 429 L to scrub 1 m^3 of this biogas.

CO_2, being an acid gas, can be absorbed in alkaline solution. The three common alkaline reagents are NaOH, $Ca(OH)_2$ and KOH. Two consecutive alkaline reactions of CO_2 removal in NaOH solution are:

$$2\ NaOH + CO_2 \rightarrow Na_2\ CO_3 + H_2O \tag{4.17}$$
$$Na_2\ CO_3 + CO_2 + H_2O \leftrightarrow 2\ NaHCO_3\downarrow \tag{4.18}$$

Figure 4.18 Biogas storage tank made of polyethylene, Rayong Municipality, Thailand (www.cogen3.net)

Figure 4.19 Co-generator run on biogas (www.cogen3.net)

Table 4.22 Quantities of biogas required for a specific application[a]

Use	Specification	Quantity of gas required ft^3/hr	m^3/hr
Cooking	2" burner	11.5	0.33
	4" burner	16.5	0.47
	6" burner	22.5	0.64
	2"-4" burner	8-16	0.23-0.45
	per person/day	12-15	0.34-0.42
Gas lighting	per lamp of 100 candle power	4.5	0.13
	per mantle	2.5-3.0	0.07
	2 mantle lamp	5	0.14
	3 mantle lamp	6	0.17
Gasoline or diesel engine[b]	converted to biogas, per hp	16-18	0.45-0.51
Refrigerator	per ft^3 capacity	1.0-1.2	0.028-0.034
Incubator	per ft^3 capacity	0.4-0.7	0.013-0.020
Gasoline	1 liter	47-66[c]	1.33-1.87[c]
Diesel fuel	1 liter	53-73[c]	1.50-2.07[c]
Boiling water	1 liter	3.9[d]	0.11[d]

[a] Compiled by NAS (1977)
[b] Based on 25 percent efficiency
[c] Absolute volume of biogas needed to provide energy equivalent of 1 L of fuel
[d] Absolute volume of biogas needed to boil off 1 L of water

Table 4.23 Approximate solubility[a] of CO_2 in water[b]

Pressure		Temperature ^oF (^0C)				
Atm	kg/cm^2	32 (0)	59 (10)	68 (20)	86 (30)	104 (40)
1	1.03	0.40	0.25	0.15	0.10	0.10
10	10.3	3.15	2.15	1.30	0.90	0.75
50	51.7	7.70	6.95	9.00	4.80	3.90
100	103	8.00	7.20	6.60	6.00	5.40
200	207	-	7.95	7.20	6.55	6.05

[a] Solubility is expressed as kg CO_2 per 100 kg H_2O
[b] Adapted from Nonhebel (1964)

$NaHCO_3$ is the precipitate form which can be removed from the solution.

Lime or $Ca(OH)_2$ is readily available in most areas and is low-cost. The reaction of CO_2 removal in lime solution is

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3\downarrow + H_2O \quad (4.19)$$

$CaCO_3$ is the precipitate needed to be removed from the solution. Based on the stoichiometry in Equation 4.19, a mixture of 1 kg burnt lime in 1 m^3 of water is sufficient to remove about 300 L of CO_2 or 860 L of biogas (assuming a CO_2 content of 35 %).

The availability of KOH is not as extensive as $Ca(OH)_2$ and its application in CO_2 scrubbing is also limited.

Hesse (1982) showed a model of lime scrubber for biogas (Figure 4.20) which was developed by Ram Bux Singh in India. A stirring paddle creates agitation which aids in the diffusion of gas molecules into the alkaline solution and extending the contact time between the liquid and the gas.

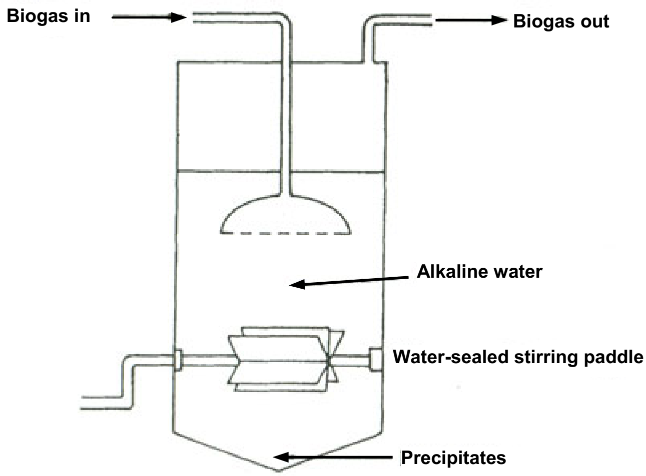


Figure 4.20 Model of CO_2 and H_2S scrubber in alkaline water

Example 4.3

Suppose the quantity of CO_2 present in biogas produced by a small digester is 3 m^3/ day. Compare the amount of water and $Ca(OH)_2$ needed to completely remove this CO_2 from the biogas.

For CO_2 density of 1.89 kg/m^3 at 20° C and 1 atmosphere pressure, the weight of CO_2 is $1.89 \times 3 = 5.52$ kg/day

For water scrubbing, based on Table 4.23, at 20° C the solubility of CO_2 is 0.15 kg/100 kg of water.

Therefore the amount of water needed for CO_2 scrubbing is 5.52 (100)/0.15 = 3,680 kg/day.

For $Ca(OH)_2$ or lime scrubbing, based on stiochiometric reactions of Equation 4.19, the amount of $Ca(OH)_2$ needed for CO_2 scrubing is 74(5.52)/44 = 9.28 kg/day or the amount of CaO needed is 7.02 kg/day.

H_2 S removal

Na_2CO_3 formed in Equation 4.17 can also be used to remove H_2S from the biogas, provided the contact time is sufficiently long for the reaction (Equation 4.20) to occur in the scrubber:

$$H_2S + Na_2CO_3 \rightarrow NaHS + NaHCO_3\downarrow \quad (4.20)$$

A simpler and more economical method of H_2S removal, when other constituents need not be removed, is to pass the biogas over iron fillings or ferrix oxide (Fe_2O_3) mixed with wood shavings (NAS 1977). This method called 'dry gas scrubber' can have a model as shown in Figure 4.21 (This model was developed by Ram Bux Singh as reported by Hesse 1982). The reaction occurring during H_2S scrubbing is:

$$Fe_2O_3 + 3\ H_2S \rightarrow Fe_2S_3 + 3\ H_2O \quad (4.21)$$

The Fe_2O_3 can be regenerated by exposing or heating Fe_2S_3 in air (or oxygen) according to the following reaction:

$$2Fe_2S_3 + 3\ O_2 \rightarrow 2Fe_2O_3 + 3\ S_2 \quad (4.22)$$

Other processes of biogas purification are available (Nonhebel 1972), but they are technically sophisticated and expensive which are not applicable to the biogas systems as described in this chapter.

4.6.2 Methanol Production

CH_4 produced from anaerobic digestion can be catalytically reacted with steam and CO_2 to yield H_2 and CO, as shown in Equation 4.23.

$$3CH_4 + 2H_2O + CO_2 \rightarrow 8H_2 + 4CO \quad (4.23)$$

The gas mixture of H_2 and CO (called syngas) is then compressed and converted to methnol (CH_3OH) according Equation 4.24.

$$8H_2 + 4CO \rightarrow 4CH_3OH \quad (4.24)$$

Methanol, a liquid fuel, has a calorific value of 5.34 kcal/g or 171 kcal/gmole. It is a poisonous liquid, but has wide applications as fuels, solvents and anti-freeze agents. The use of methanol as an automotive fuel has the following advantages such as: reduced emission of hydrocarbons, particulate matters and toxic compounds, increased fire safety (because methanol is less flammable than gasoline) and reduced dependence on imported oils. More than 10,000 methanol passenger cars and buses are currently in use and the number is expected to increase in the years to come.

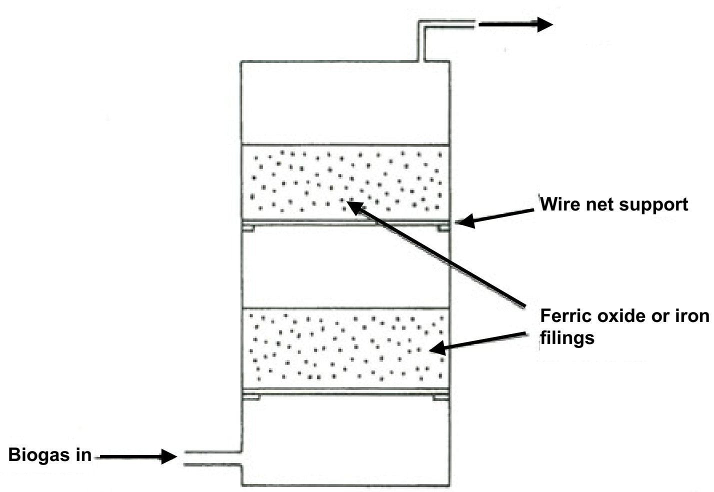


Figure 4.21 Model of dry gas scrubber for H_2S removal

4.6.3 Digested Slurry

Although there is a considerable degree of reductions of organic, solid and nitrogenous matters in anaerobic digesters, digester slurry still contains high concentrations of the above matters (see Table 4.9) which should be treated further prior to disposal. The digester slurry also contains various types of pathogens (as stated in section 4.1), requiring great care in the handling and disposal. On the other hand, high nutrient contents in the slurry make it suitable to be reused such as compost fertilizer (Chapter 3) and in application to fish ponds (Chapter 6) or on land (Chapter 9).

4.7 ETHANOL PRODUCTION

4.7.1 Objectives, benefits and limitations

This section describes the principles of ethanol (C_2H_5OH) production by fermentation of organic wastes and other biomass, such as molasses, sugarcane, cassava and corn. Ethanol is a liquid fuel which, due to the increasingly high oil price, is being produced in several countries for use as an alternative source of energy. Since these organic materials contain high BOD concentrations, fermenting them to produce liquid fuel would yield economic return and help reducing pollution problems that could occur if they are improperly disposed off to the water or land environment.

Table 4.24 compares ethanol yields from the four types of biomas raw materials. Molasses and corn give relatively high ethanol yields of 280 and 310 L/ton, respectively; while, based on land area, sugarcane gives the highest ethanol yield of 3,500 – 4,000 L/(ha-yr). Figure 4.20 describes the basic ethanol production process which indicates that for starch-containing biomass (such as cassava and corn), the carbohydrates need to be biochemically converted into simple sugars ($C_6H_{12}O_6$) first by alpha-amylase and gluco-amylase enzymes. Through the reactions of yeast *Saccharomyces cerevisae*, sugars are then biochemically converted to ethanol. Theoretically, 1 g of $C_6H_{12}O_6$ can produce about 0.5 g of C_2H_5OH (Figure 4.23).

It can be seen from Table 4.24 and Figure 4.23 that, based on economic and technical aspects, sugarcane is among the most attractive biomass materials to be used for ethanol production. Not only that sugar is easily converted by yeast to become ethanol, the sugar manufacturing process also produces bagasse as a by-product (section 2.3.3), which can be burnt to generate heat and steam needed for the ethanol fermentation and distillation processes. Molasses produced from the sugar manufacturing process (Figure 2.6) and contained mostly $C_6H_{12}O_6$ can also be easily converted, through the yeast reaction, to become C_2H_5OH.

Table 4.24 Ethanol yields from selected biomass raw materials (adapted from NRC 1983)

Biomass raw materials	Ethanol Yield (L/ton)	Raw materials yield tons/(ha-yr)	Ethanol yield L/(ha-yr)
Sugarcane	70-90	50-90	3,500-8,000[a]
Molasses	280	NA	NA
Cassava	180	12-60[a]	2,000-5,000[a]
Corn	370	6	2,220

NA = Not applicable

[a] potential yields with improved cultivation technology

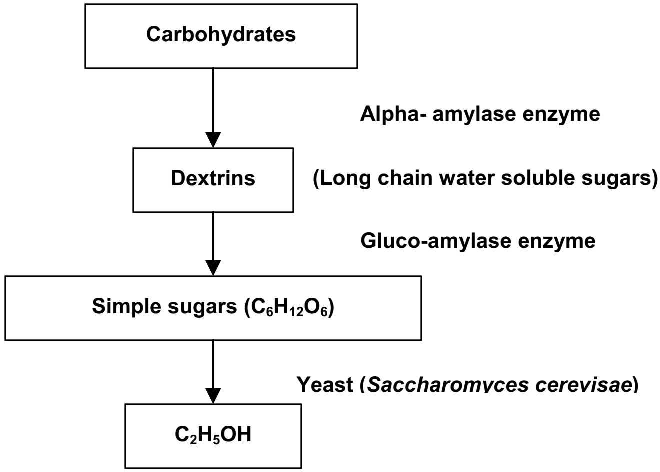


Figure 4.23 Ethanol production process

Some limitations of ethanol production from biomass raw materials include:

- Competition for land to be used for food crops and energy crops. As several economically developing countries are not self sufficient in food production, too much cultivation of these biomass raw materials for ethanol production may lead to reduced land area available for cultivation of food crops for human and animal consumption.
- Land degradation and loss of soil fertility. Because they are high yield crops, if without proper soil management, land areas used for growing these biomass raw materials may lose soil fertility in a short period of time.

4.7.2 Ethanol production process

The production of ethanol from biomass raw materials normally involves; storage and preparation of the raw materials, fermentation, distillation and drying and ethanol storage. A brief description of the above process is given below.

Storage and preparation of raw materials

Because most crops (as shown in Table 4.24) are normally harvested once a year, to provide for year-round operation of ethanol fermentation plants, the harvested raw materials have to be properly stored to avoid loss of carbohydrates through spoilage, sprouting or (in temperate climate) freezing. This is generally done by storing the raw materials in rooms equipped with proper ventilation or drying to reduce the moisture content. For sugarcane, it is advisable to extract the juice syrups from the crops by crushing or pressing and concentrate them to about 20-24% sugar content to avoid microbial growth.

Except the sugarcane juice or molasses which contain readily fermentable sugar compounds ($C_2H_{12}O_6$), the starch-containing materials such as cassava and corns contain large amount of simple sugars bound up in complex molecules of carbohydrates, not easily fermentable. To break down these complex carbohydrates molecules, cassava or corns have to be milled or grinded and water is added to form slurry containing about 65% water content. The slurry is then heated to 65 – 93^{o}C (150-200^{o}F) and an enzyme alpha-amylase is added to convert the starch to become long chain water soluble sugars called dextrins ($C_6H_{10}O_5$). These dextrins are further converted to simple sugars ($C_6H_{12}O_6$) by an enzyme gluco-amylase at temperature of 60^{o}C (135-140^{o}F).

Fermentation

Ethanol fermentation is a complex process accomplished biochemically by yeast, *Saccharomyces cerevisae,* according to the following simplified equation:

$$\underset{\text{Simple sugar}}{C_6H_{12}O_6} \rightarrow \underset{\text{ethanol}}{2C_2H_5OH} + 2\ CO_2 + \text{heat} \tag{4.23}$$

Theorectially, from Equation 4.23, 1 g of $C_6H_{12}O_6$ produces about 0.5 g of C_2H_5OH, but actual C_2H_5OH yield at fermentation is less because about 5% of sugar is used by the yeast to produce new cells and other by-products such as glycerols, acetic acid and lactic acid etc.

For the ethanol fermentation or the yeast reaction to proceed at an optimum rate, the following environmental conditions as summarized in Table 4.25 should be maintained in the fermenter:

- Sugar concentration should be controlled at 20 %. Too high sugar concentrations can inhibit the growth of yeast cells in the initial stage of fermentation, or they can result in too high ethanol concentration more than 10 % in the fermenter which are also toxic to the yeast cells.

- Nutrient requirements, such as N, P, K, essential for yeast growth, have to be provided.
- The optimum temperatures for *Saccharomyces cerevisae* are 27-35°C. Fermentation rates will decrease at temperatures above 35°c and will stop at temperature above 43°C. Temperatures below 27°C will also decrease the fermentation rates. In general, the fermentation period is 2-3 days to produce an ethanol concentration of 8-10%.
- Contamination of the fermenters with other microorganisms (such as bacteria) should be avoided because bacteria will also utilize sugar for their growth, resulting in less ethanol production.
- Since *Saccharomyces cerevisae* grow best at pH range 4-6, this pH level (about 5) should be maintained in the fermenters.

Table 4.25 Environmental conditions for ethanol fermentation

Design parameters	Optimum values
Sugar concentration	20%
Temperature	27-35°C
Fermentation period	2-3 days
pH range	4-6

Distillation and drying

In general, the fermented ethanol will contain about 10 % ethanol and 90 % water and other by-products. Distillation process is usually employed to produce about 96% pure ethanol which is the highest ethanol solution that can be recovered by simple distillation (called azeotropic condition where the relative volatilities of ethanol and water are the same). The 96% pure ethanol solution can be used in various applications such as fuel in engines and disinfectants, etc.

Ethanol drying is done to further remove the remaining 4% water content before its use as a blend with gasoline or as fuel for engines and automobiles. Three proven methods of ethanol drying include: azeotropic distillation (in which some compounds such as benzene are added to change the relative volatilities of the ethanol/water mixture); adsorption of water by the reactions of dessicants, such as CaO; and molecular sieving of the water molecules by some zeolites.

Figure 4.24 is a schematic diagram showing the process of ethanol production from cassava. In addition to ethanol, other valuable by-products are also produced which are applicable for agricultural and aquacultural reuses.

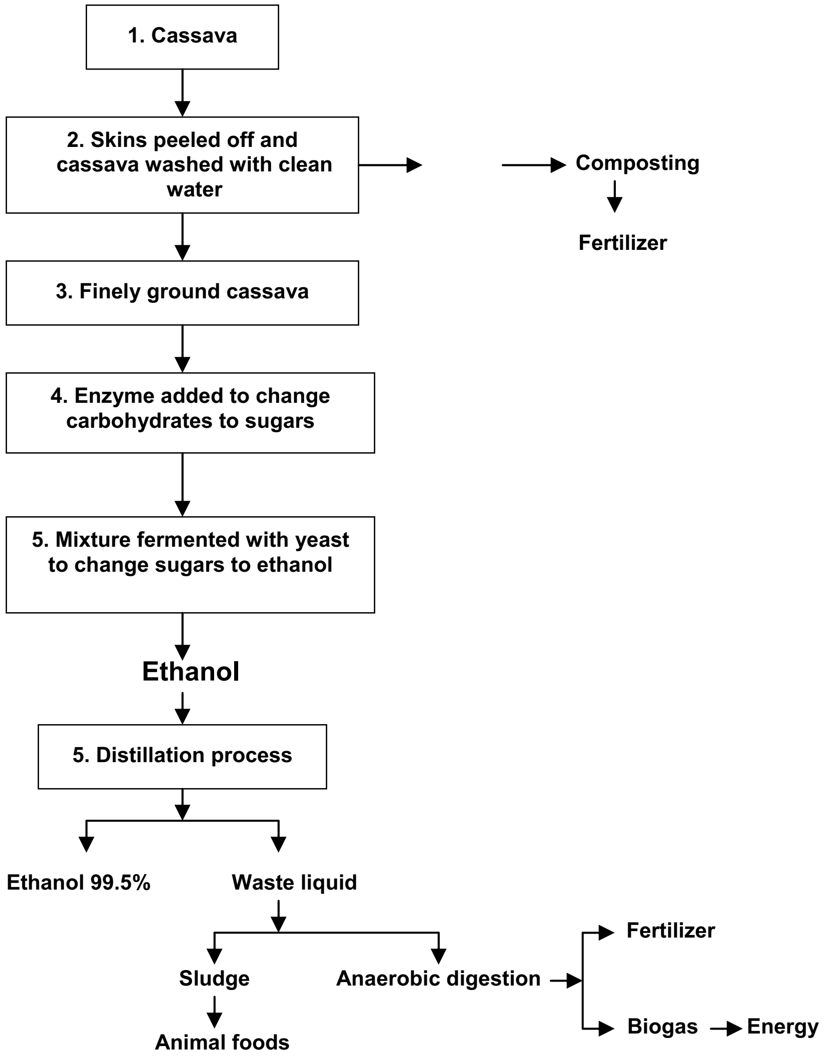


Figure 4.24 Ethanol production from cassava

Because ethanol distillation and drying require capital investment and are energy intensive, more research in these areas should be undertaken to reduce the cost of ethanol production and make it economically feasible for wider applications.

Due to the high oil prices, world ethanol production has been increasing as shown in Table 4.26, with Brazil and U.S.A. being the largest producers. Millions of car that can use gasoline and ethanol interchangeably have been sold in Brazil, U.S.A., and elsewhere. These cars can use up to 85% ethanol, compared with 10% ethanol blend with gasoline for normal cars. Case studies of ethanol production programs in Brazil and U.S.A. are given below:

4.7.3 Case Studies of ethanol production

U.S.A. (Renewable Fuel Association 2006)

In the year 2005, ethanol production in the U.S.A. was 16.14 million m^3. The major raw material was corns which are grown mainly in the mid-west states. Due to the high oil prices, the rates of ethanol production has been on the increasing trend, from 0.66 million m^3 in 1980 to 16.14 million m^3 in 2005, equivalent to a gross output of US$ 32.2 billion against the investment costs for corns and other grains and operation-related activities of US$ 5.1 billion. It is expected that in the year 2012 ethanol production in the U.S.A. will result in: reduced crude oil imports of 2 billion barrels, creating 234,840 new jobs in the ethanol production industry and increased household income by US$ 43 billion.

Table 4.26 World ethanol production[a] (Renewable Fuel Association 2006)

Countries	2004	2005
Brazil	15.10	16.00
U.S.A.	13.38	16.14
China	3.65	3.80
India	1.75	1.70
France	0.83	0.91
Russia	0.75	0.75
South Africa	0.42	0.39
UK	0.40	0.35
Thailand	0.28	0.30
Others	4.21	5.65
Total	40.76	45.99

[a] Millions of m^3

Brazil (Wikipedia 2006)

Ethanol production in Brazil in 2005 was 16 million m^3, about the same as those in U.S.A., but sugarcane is the major raw material used in ethanol fermentation. Land used in sugarcane plantation is 45,000 km^2 and annual sugarcane production is 344 million tons. Half of the harvested sugarcane is used for sugar production, while the other half is used for ethanol production. From 1978 to

2005, ethanol production in Brazil was found to increase about 3-4% annually. Presently, the use of ethanol as fuel by Brazillian cars - as pure ethanol and in gasohol – replaces gasoline at the rate of about 27,000 m^3 per day or about 40% of the fuel needed for the vehicles running on gasoline alone. Ethanol uses have resulted in improved air quality in big cities due to better combustion efficiency and also in improved water quality because ethanol (which is easier to be biodegraded) replaces some toxic compounds of the gasoline. However, there are reports of negative environmental impacts results from extensive ethanol production from sugarcane. These include: reduced areas of food-growing fields, social-economic effect on the poor farmers who have to give up food-crop lands for biofuel production.

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4.9 EXERCISES

4.1 a) You are to visit a biogas digester located at a farm or at a wastewater treatment facility, and find out the organic loading rate, HRT, and biogas (CH_4) production rate. Compare these data with those given in Table 4.11 or 4.14. Discuss the results.

b) Also check with the biogas digester operator about the common problems of the digester and the remedial measures employed to solve these problems.

4.2 A farm has 100 cattle, each producing 40 L manure/day with 12.5% total solids (125 kg TS/m^3), volatile solids (VS) is 75%TS and a C/N ratio of 15. The manure is to be used for biogas production together with rice straw, which has a C/N ratio of 80, moisture content of 50%, VS is 80%TS, bulking density of 0.5 kg/L and N content of 0.9% dry weight. How much rice straw is needed to be mixed with the cattle manure to reach a C/N ratio of 25? At the VS loading of 2 kg/m^3-day and an HRT of 40 days, determine the volume of the biogas digester and the volume of dilution water required to mix with the manure.

4.3 A biogas digester produces 5 m^3 of biogas per day, which contains 35% of CO_2 by volume. The density of CO_2 is 1.80 kg/m^3 at 25°C and 1 atmosphere pressure. Determine the daily requirement for quicklime (containing 95% CaO) to remove the CO_2.

4.4 A 1000-pig farm plans to purchase 8-m^3 PVC bag digesters to produce biogas using pig wastes in its own stock. Each pig weighs 80 kg. The loading rate of the bag digester and HRT recommended by the producer are, respectively, 1.5 kg VS/m^3-day and 30 days for pig wastes diluted with water. Other data are available in Table 2.7. Determine the number of bag digesters that should be installed to treat the pig wastes and the amount of biogas to be produced if the biogas production rate is 0.3 m^3/kg VS added. If the density of the pig wastes is 1.1 kg/L, what is the volume of dilution water required?

4.5 Differentiate the hydraulic patterns and treatment mechanisms occurring in an anaerobic filter and an upflow sludge blanket reactor.

4.6 A farmer in a rural area in northern Thailand plans to use cattle manure to produce about 5 m^3/day of biogas for domestic use.

a) Determine the size of the biogas digester, the amount of cattle manure to be added to the biogas digester and the amount of water dilution (if necessary), in order to produce the required amount of biogas.
b) If the biogas contains 30% CO_2 (by volume), determine the amount of $Ca(OH)_2$ needed to completely remove CO_2 from the biogas. How much sludge is produced from this CO_2 removal operation and how should this sludge be handled by the farmer?

Given: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

c) If the farmer wants to produce ethanol from his cattle manure, based on theoretical knowledge given in section 4.7, explain how it can be done. Draw schematic diagram.
d) If you are to advise this farmer on the production of biofuel from cattle manure, would you advise that he produce biogas or ethanol? Give reasons.

The following information are given:

For cattle manure:
VS content = 300 kg/m^3 of manure (wet weight)

For biogas digester:

Organic loading rate	= 3 kg VS/(m^3-day)
Hydraulic retention time	= 30 days
Biogas production	= 0.3 m^3/kg VS added

For biogas purification

Density of CO_2 = 1.5 kg/m^3 at 1 atmosphere and ambient temperature

4.7 A cattle farm in rural Thailand needs 10 m^3 of CH_4 gas daily for cooking and heating purposes. The farmer plans to construct a biogas digester using cattle manure as the raw material.

a) Determine the size of the biogas digester to be built, the amount of cattle manure to be fed daily to the biogas digester and the amount of water dilution (if necessary), in order to produce the required CH_4 gas. Draw a schematic diagram of this biogas digester.

The following information are given:

For biogas digester design and operation:

Organic loading rate	= 3 kg VS/(m^3-day)
Hydraulic retention time	= 20 days
CH_4 production	= 0.2 m^3/kg VS added

For cattle manure:

Total solids (TS) content	= 10%
Volatile solids (VS) content	= 90% of TS
Bulk density	= 1.1 kg/L

b) Suppose CO_2 production from this biogas digester is 3 m^3/day. To increase the heating value of the biogas, the farmer plans to use water scrubbing to remove CO_2.

You are to determine the amount of water needed to completely remove this CO_2 gas and the size of the water scrubber, if the scrubbing water is to be replaced once a week. Draw a schematic diagram of this water scrubber and suggest method to handle the effluent from the water scrubber.

The following information are given:

Water temperature	= 20°C
Solubility of CO_2 in water	= as given in Table 4.23
Density of CO_2	= 1.8 kg/m^3 at 20°C and 1 atmospheric pressure
Density of H_2O	= 1 kg/L at 20°C and 1 atmospheric pressure

c) If $Ca(OH)_2$ is to be used for CO_2 removal, determine the daily amount of $Ca(OH)_2$ required and the daily amount of precipitates to be produced. How to handle or reuse the precipitates?

4.8 With the high oil prices, you are to explore the agricultural raw materials being grown in your country which are suitable for ethanol production. Based on the available data, estimate the gross ethanol production and the economic gains to be achieved from the ethanol production.

4.9 You are to evaluate alternative energy sources that can be produced in your country and recommend measures to increase the production of these alternatives. Your recommendation should be based on technical capability and socio-economic conditions of your country.

5
Algal production

Algae are diverse group of microorganisms that can perform photosynthesis. They range in size from microscopic unicellular forms smaller than some bacteria to multicellular forms such as seaweeds that may become many meters in length. Unicellular algae are collectively called phytoplankton or single cell protein (e.g. green algae, blue-green algae) and these are main interest in the waste treatment and recycling processes because they are tolerant to change in environmental conditions.

Botanists generally classify algae on the basis of (1) their reproductive structures, (2) the kind of products synthesized and stored in the cells, and (3) the nature of the pigments in the chromatophores. There are seven phyla of algae as shown in Table 5.1, and examples of some planktonic algae are given in Figure 5.1.

In most algal species the cell wall is thin and rigid. Cell walls of diatoms are impregnated with silica, making them rather thick and very rigid. Walls of blue-green algae contain cellulose and are semi-rigid. The motile algae such as the euglena have flexible cell walls. The cell walls of most algae are surrounded by a flexible, gelatinous outer matrix secreted through the cell wall. As the cells age, the outer matrix often becomes pigmented and stratified, developing into a semi-rigid surface membrane.

Of the seven phyla shown in Table 5.1, the largest division of algae is the Chlorophyta or green algae. The photosynthetic ability of algae enables them to utilize sunlight energy to synthesize cellular (organic) material in the presence of appropriate nutrients. Thus the algae (and also the bacteria) are the major primary producers of organic matter in aquatic environment.

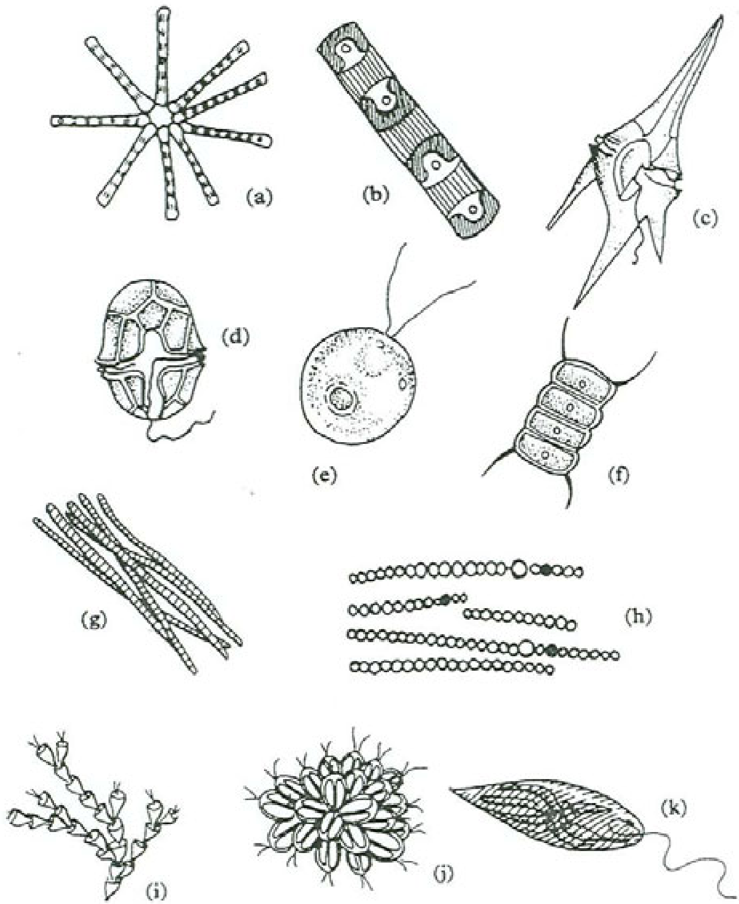

Figure 5.1. Examples of planktonic algae. Diatoms: (a) *Asterionella*; (b) *Skeletonema*. Dinoflagellates: (c) *Ceratium* and (d) *Peridinium*. Green Algae: (e) *Chlamydomonas*; (f) *Scenedesmus*. Blue-green algae: (g) *Aphanizomenon* and (h) *Anabaena*. Chrysophytes: (i) *Dinobyron* and (j) *Synura*. Euglenoids: (k) *Euglena.*

Table 5.1 Summary of the major phyla of algae (adapted from Mitchell 1974)

Phylum	Common name and species	Pigmentation	Other characteristics
Cynophyta	Blue green algae; *Spirulina, Oscillatoria, Anabaena*	Blue-green; phycocyanin, phycoerythrin chlorophyll *a* and *b*	Multicellular or unicellular but usually microscopic; some forms become unicellular in turbulent media; usually with gelatinous sheath
Euglenophyta	Euglenoids; *Euglena*	Grass green	Unicellular motile; lacking cell wall
Chlorophyta	Green algae; *Chlorella, Oocystis, Scenedesmus*	Grass green Chlorophyll *a* and *b*	Unicellular or multicellular; a few microscopic; cell wall of cellulose and pectins
Chrysophyta	Yellow green or golden brown algae (diatoms); *Diatoma, Navicula, Asterionella*	Yellow green to golden brown; xanthophylls and carotenes may mask the chlorophyll. Chlorophyll *a* and *c*	Microscopic, mostly unicellular; includes the large group of diatoms which have a cell wall containing silica
Pyrrophyta	Some are dinoflagellates; *Peridinium, Massarita*	Yello green to dark; xanthophylls predominant. Chlorophyll *a* and *c*	Unicellular motile; cellulose cell wall
Phaeophyta	Brown algae; *Fucus*	Olive green to dark brown; fucoxanthin and other xanthophylls predominant Chlorophyll *a* and *c*	Principally multicellular and marine (sea weeds) cellulose and pectin cell wall
Rhodophyta	Red algae; *Polysiphonia*	Red; phycocyanin, phycoerythrin. Chlorophyll *a*	Some unicellular, mostly multi cellular; marine-cellulose and pectin cell wall

5.1 OBJECTIVES, BENEFITS AND LIMITATIONS

With respect to algal mass culture in wastewater, efforts have been directed towards single cell protein production for potential human and animal consumption. The desirable properties of algal single cell protein are:

- High growth rate
- Resistance to environmental fluctuations
- High nutritive value
- High protein content
- Ability to grow in wastewater

The production of algal biomass from wastewater has the following objectives and benefits:

5.1.1 Wastewater treatment and nutrient recycling

The biological reactions occurring in the algal ponds reduce the organic content and nutrients of the wastewater by bacterial decomposition, and convert them into algal biomass by algal photosynthesis. Algal cells have high protein value, and subsequent harvesting of algae for human and animal consumption will be the financial incentive to wastewater treatment. The average production of algae is reported as 70 tons/(ha-yr) or 35 tons/(ha-yr) algal protein; comparing with the productivity of conventional crops, wheat 3.0 (360 kg protein), rice 5.0 (600 kg protein) and potato 40 (800 kg protein) tons/(ha-yr) (Becker 1981).

Almost all the organic wastes such as municipal wastewater, agricultural and animal wastes can be treated by the algal systems, resulting in considerable algal biomass yields.

5.1.2 Bioconversion of solar energy

Solar energy is the primary source of energy for all life. This energy is utilized by phytoplankton during photosynthesis and synthesis of new cell occurs. Algae are phytoplankton and they are the primary producers in the food chain with high productivity. Therefore algal production will be the efficient method of conversion of solar energy.

5.1.3 Pathogen destruction

Wastewater usually contains pathogens that are harmful to human. Therefore pathogen destruction with waste stabilization is advantageous in waste recycling process. Some magnitude of pathogen destruction occurs in algal ponds due to adverse environment prevailing in the pond. Adverse environment to pathogens is caused by:

- Diurnal variation of pH due to photosynthesis,
- Algal toxins excreted by algae cells, and
- Most importantly, solar radiation (UV light)

At present, the main attractiveness of algal mass cultures is that they have great versatility to be integrated into multi-use systems for simultaneously solving several environmental problems. Figure 5.2 shows possible applications of the algal mass cultures, the details of which are described in section 5.4.

Since algal mass culture systems must be large and exposed to the outdoor environment, it greatly magnifies the bioengineering problems involved. Specific problems relating to culture mixing, nutrient availability and addition, species control, algal separation and harvesting have been of major concern, as outlined below.

Harvesting

Algae are very small in size (ranging from 1 to several μm), difficult to harvest and requiring skilful operation. The existing technologies of algal harvesting are normally complex and expensive, and will be discussed in section 5.3.

The economical method of harvesting of algal cells from algal pond is still under research.

Algae composition

Except *Spirulina*, algae have thick cell wall, which makes the untreated algae indigestible to non-ruminants. Therefore before feeding to animals, algae cells have to be ruptured by:

- Chemical alteration of cell wall by acid treatment, or
- Mechanical or thermal treatment for cell wall destruction.

Another factor limiting the consumption of waste-grown algae is nucleic acid present in algae cells (4-6%), which may be harmful to human bodies (Becker 1981).

To produce algal biomass for animal or human consumption, the blue-green algae, *Spirulina* (Figure 5.3), is the desirable species to be cultured because its cell wall is more digestible by non-ruminants and its filamentous cells are easier to be harvested. Mass culture of pure species of *Spirulina* requires certain environmental conditions (e.g. pH and nutrients) conducive to its growth without contamination from other microbes. Algal ponds or high-rate ponds treating wastewater will contain several algal and bacterial species essential for wastewater treatment. (The term 'high-rate' is commonly used for algal ponds because algal growth rate in these ponds is several times greater than that occurring in conventional waste stabilization ponds whose objective is mainly waste treatment. Details of the high-rate ponds are given in section 5.2.) The waste-grown algae thus need to be processed further prior to being employed as human or animal feed. These algae can be used for other purposes as shown in Figure 5.2 and section 5.4.

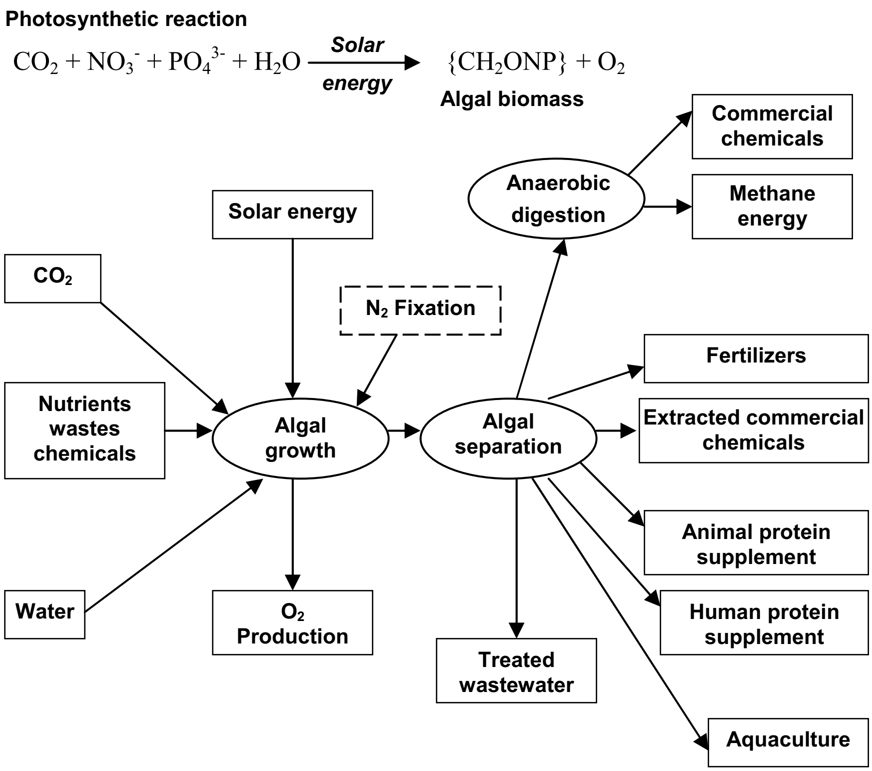

Figure 5.2 Possible applications of algal mass cultures (from Goldman 1979a; reproduced by permission of Pergamon Books Ltd)

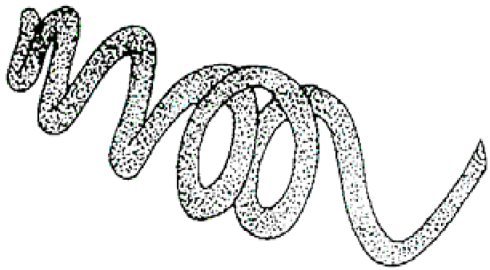

Figure 5.3 *Spirulina* “jeejibai”, showing tapering of end turns, (magnification × 600)

Contamination of toxic materials and pathogens

Possible contamination of algae with toxic substances (heavy metals, pesticides) and pathogens, which are common in wastewater, will reduce the potential value of the algal production.

5.2 ALGAL PRODUCTION AND HIGH-RATE ALGAL POND

There are three possible algal cultivation and processing systems, depending on the raw material used and the utilization of the obtained biomass (Becker 1981):

- System in which selected algal strain is grown using fresh water, mineral nutrients and additional carbon sources. The algae produced in such systems are utilized mainly as human food.
- System in which sewage or industrial wastewater is used as culture medium without addition of minerals and external carbon. In such system algal population consists of several species in the presence of high amount of bacteria. The main purpose of this system is wastewater treatment and biomass produced as feed for animals or as substrate for energy production.
- System where cultivation of algae in an enclosed system (fermenter) under sunlight or artificial light, with cells being grown in a completely autotrophic medium.

System (b) is related with our objectives of waste treatment, recovery and recycling and will be the main concern in this chapter.

The basic reactions occurring in an algal pond can be represented by Equations 2.1, 2.2 and 2.6 or the "algal-bacterial symbiosis" previously cited in section 2.4. These reactions are schematically shown in Figure 5.4. Organic matter entering the system as wastewater or sludge is aerobically decomposed by bacteria, using oxygen produced by algal photosynthesis. The algae, utilizing solar energy and nutrients (or by-products) from the bacterial oxidation, perform photosynthesis and synthesizing new algal biomass. It is apparent from Figure 5.4 that the excess biomass of algae and bacteria produced during the algal-bacterial symbiosis needs to be regularly removed from the system to maintain a constant biomass and efficient performance of the system.

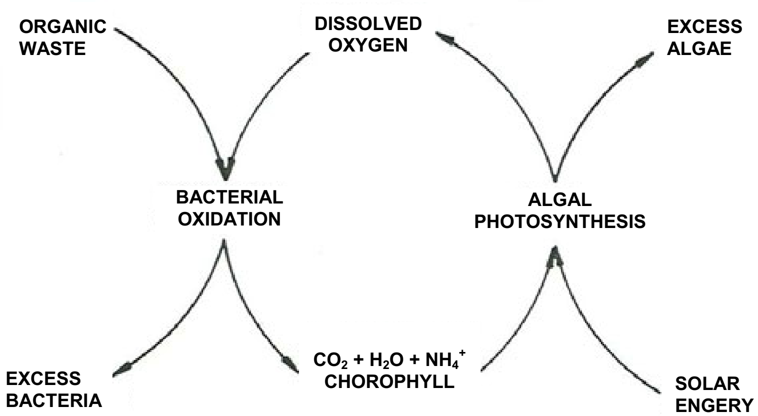

Figure 5.4 The cycle of oxygen and algal production in sewage treatment by photosynthesis (from Oswald and Gotaas 1955; reproduced by permission of the American Society of Civil Engineers)

5.2.1 High-rate algal pond (HRAP) systems

The HRAP conventionally takes the form of a continuous channel equipped with an aerator-mixer to re-circulate the contents of the pond. It is characterized by large area/volume ratios, and shallow depths in the range of 0.2-0.6 m to allow sunlight to penetrate the whole pond depth. To minimize short-circuiting, baffles are normally installed in the pond to make the length/width ratio of the channel greater than 2/1. A diagram and photograph of HRAP are shown in

Figures 5.5 and 5.6. Depending on the mode of operation, sewage can be fed to the HRAP continuously or intermittently, i.e. 12 hours per day during sunlight period. HRAP is not sensitive to daily fluctuations in loading rate. Effluent overflow from HRAP, containing high algal suspension, normally goes into an algal separation unit. The effluent obtained, after the algae have been separated, is expected to have BOD_5 of 20 mg/L and DO of 0.5 mg/L. The effluent may be used for various purposes such as irrigation, industrial cooling, or recreational purposes. Because of these advantages, HRAP has in recent years received increasing attention as a means of both treating wastewater and producing algal biomass.

Factors affecting the performance of HRAP and algal production include available carbon and nutrient sources, temperature, light intensity, mixing or agitation, pond depth, and hydraulic retention time (HRT). It is generally known that light intensity is the important factor for photosynthesis and therefore algal production. Temperature influences the biodegradation rate of the organic matter, and consequently the HRT to be designed for HRAP.

In the context of photosynthesis, illuminance and irradiance are the two terms commonly used to express light intensity. Illuminance, or luminous intensity, is defined as luminous flux per unit area and bears a photometric unit of lux (lumen/m^2) or foot-candle (1 ft-candle = 10.764 lux), which can be measured by a lux meter or foot-candle meter. Irradiance, or radiant intensity, is defined as quantity of energy that is received on a unit area of surface over time and bears a radiometric energy unit of calorie per area per time, for example, gcal/cm^2-day (also called Langley/day), which can be measured by an actinometer or a pyranometer. Table 5.2 gives conversion factors for the most commonly used units of irradiance. It should be noted that illuminance and irradiance may not be directly correlated or convertible, depending on several factors such as location on the earth, latitude, season, and other meteorological effects. Some reported energy equivalents of illuminance and irradiance in the visible range of daylight (400-700 nm wavelengths) are shown in Table 5.3, where only ft-candle and gcal/cm^2-day are used for the convenience of comparison.

Only solar radiation of wavelengths between 400 nm and 700 nm is available for photosynthesis by green plants and algae, coinciding with the range of wavelengths visible to the human eye. The daily amount of solar energy that reaches the earth and water surface depends on astronomical, geographical, and meteorological factors. The maximum illuminance measured on the earth surface is about 20,000 ft-candle while the total solar irradiance (TSI) is about 1370 W/m^2. As the earth surface absorbs about 70 % of TSI and the visible light intensity within the wavelengths of 400-700 nm is about 40 % of TSI, the maximum light intensity available for algal photosynthesis is approximately 385

W/m^2, or about 790 gcal/cm^2-day. Nowadays, information of illuminance and irradiance can be obtained from meteorological data of the local weather bureau.

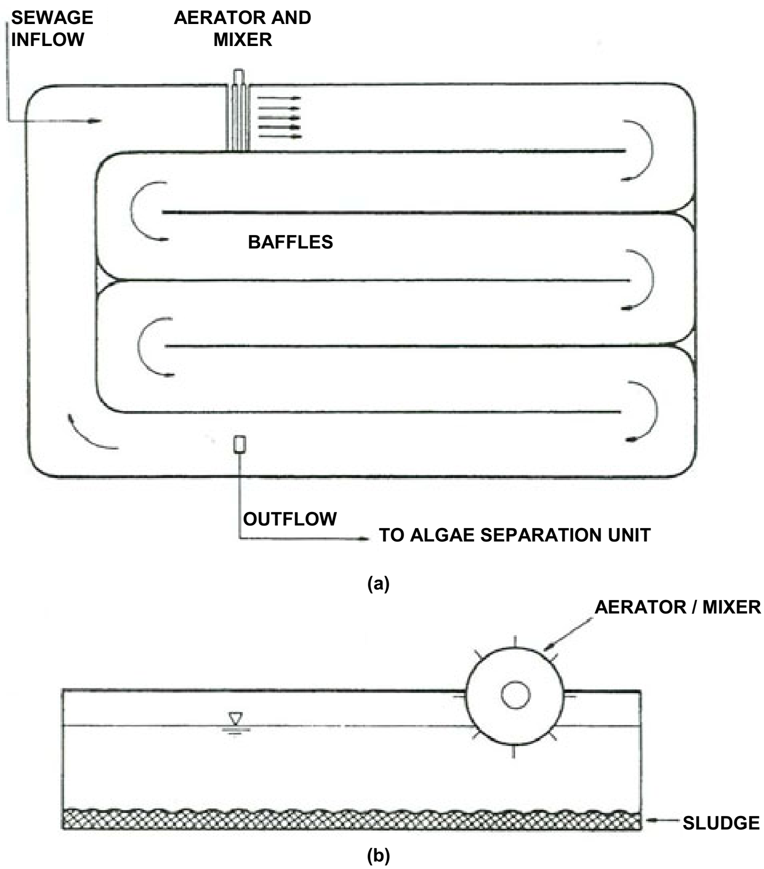

Figure 5.5 High-rate algal pond: (a) schematic plan, (b) schematic cross-section

Some illuminance and irradiance data of Bangkok city, Thailand are given in Table 5.4.

Figure 5.6 High-rate algal pond at Royal Chitrlada Palace, Bangkok, Thailand

Table 5.2 Conversion factors for the most commonly used units of irradiance

Units	gcal/(cm^2- day)	watt/m^2 (or joule/(m^2-sec))	Btu/(ft^2-hr)
gcal/(cm^2-day)	1	0.485	0.154
watt/m^2 (or joule/(m^2-sec))	2.06	1	0.317
Btu/(ft^2-hr)	6.51	3.155	1

The engineering factors that can be controlled in the design and operation of HRAP are described below.

Nutrients

Algae utilize ammonia as the principal source of nitrogen with which to build their proteinaceous cell material by photosynthetic reaction (Equation 2.6). At moderately long HRT of 3 days or 4 days when temperature and light are optimum, almost all the ammonia nitrogen appears in the form of algal cell material (Oswald and Gotaas 1955). The nitrogen content of a waste material places an upper limit on the concentration of algal cells to be developed from it.

Since about 80% of nitrogen is the waste is recovered in the algal cells (C_a) and algal cells contain approximately 8% nitrogen (N), a relationship of C_a = 10 N has been proposed. This relationship suggests that a wastewater containing 20 mg/L of N will yield an algal concentration of about 200 mg/L in HRAP, and that N in domestic sewage might become a limiting factor for algal growth if C_a exceeds 200 mg/L. To maintain efficient performance of HRAP in waste stabilization and algal biomass production, the excess algal biomass has to be regularly removed or harvested as previously mentioned.

Table 5.3 Reported energy equivalents of illuminance and irradiance in the visible range of daylight (400-700 nm wavelengths)

Energy equivalents	Reference
1 ft-candle = 0.0206 gcal/(cm^2-day)	Kreith and Kreider (1978)
1 ft-candle = 0.0936 gcal/(cm^2-day)	Wetzel and Likens (1979)
1 ft-candle = 0.0913 gcal/(cm^2-day)	Golterman (1975)
1 ft-candle = 0.0933 gcal/(cm^2-day) (daylight, full sun)	Coombs and Hall (1982)
1 ft-candle = 0.1119 gcal/(cm^2-day) (blue sky light)	Coombs and Hall (1982)
1 ft-candle = 0.072 gcal/(cm^2-day)	Bickford and Dunn (1972)

Table 5.4 Illuminance and irradiance data for Bangkok, Thailand (25th February 2006)

Time of day	Temperature (°C)	Illuminance (ft-candle)	Irradiance [a] (gcal/(cm^2-day))
7:00 am	21	360	80
12:00 pm	37	6450	1370
5:00 pm	36	870	230

[a] the visible light intensities are about 40% of these measured values

Phosphorus (P), important to algal growth, is not expected to become a limiting factor because of increased use of detergents in the home and industries. Other nutrients, such as magnesium (Mg) and potassium (K), should be presented in domestic sewage in sufficient quantities to support the growth of algae in HRAP. The percent contents of P, Mg, and K in algal cells are 1.5, 1, and 0.5, respectively (Oswald and Gotaas 1955).

Depth

Pond depth should be selected on the basis of the availability of light to algae. Oswald and Gotaas (1955) suggested that it might be approximated by Beers-Lambert law:

$$\frac{I_z}{I_i} = \exp(C_a.\alpha.z) \tag{5.1}$$

Where,

I_i = the measured light intensity at the pond surface, varying from 0 to 20,000 ft-candle

I_z = the measured light intensity at depth z, ft-candle

α = the specific absorption coefficient, ranging from $1x10^{-3}$ to $2x10^{-3}$

C_a = the concentration of algae, mg/L

z = pond depth, cm

For practical design it should be assumed that all available light is absorbed; therefore, at the pond bottom the transmitted light, I_z, should be relatively small. If I_z is taken as equal to 1, Equation 5.1 can be written as:

$$z = \frac{ln\ I_i}{C_a.\alpha} \tag{5.2}$$

Equation 5.1 defines the effective depth for photosynthetic oxygen production in as much as there is no visible light and, hence, no algal growth below depth z.

To determine z for an HRAP, the values of I_i, C_a and α have to be selected. I_i values can be obtained from meteorological data of that particular area which will vary as seasons, climate and latitude, normally from a few hundred ft-candles to more than 10,000 ft-candles. C_a concentrations in HRAP are between 200 and 300 mg/L. The value of α depends on the algal species and their pigmentation, which practically may be taken as $1.5x10^{-3}$.

It appears from Equation 5.2 that C_a is the only controllable parameter, which determines optimum pond depth for an HRAP. Theoretically, the depth for maximum algal growth should be in the range of from 4.5 to 5 in. (about 12.5 cm). Oswald (1963) carried out laboratory and pilot-scale experiments and found the optimum depth to range from 8 to 10 in. (20 to 25 cm). However from a practical point of view, the depth should be greater than 20 cm (i.e. 40-50 cm) to allow for the sludge layer and for maintaining the needed HRT (Moraine *et al.* 1979).

Example 5.1

A municipality in Southeast Asia produces wastewater with the following characteristics:

Flow rate = 2000 m^3/day
BOD_5 = 100 g/m^3
NH_3-N = 20 g/m^3

If this wastewater is to be applied to an HRAP to produce algae density (C_a) of 200 g/m^3, determine the following:

a) suitable dimensions (depth x width x length) of the HRAP and the algal productivity to be obtained, assuming the optimum HRT is 5 days, I_i is 10,000 ft-candle and $\alpha = 10^{-3}$.
b) if it is desired to double the algal productivity from this wastewater, what measures can be done to achieve this objective?

a) From Equation 5.2,

$z = \ln (10{,}000)/(200 \times 10^{-3}) = 46.05$ cm
Volume of HRAP = 2000 × 5 = 10,000 m^3
Surface area of HRAP = 10,000/0.46 = 21,739 m^2

To allow for sludge layer and freeboard, the recommended dimensions (depth × width × length) are 0.8 × 100 × 200 m^3.

Note: To provide plug-flow and mixing conditions, baffles need to be placed in the HRAP similar to that shown in Figure 5.5.

The algal productivity is 2000 × 200 = 400 kg/day

b) To double the algal productivity, C_a has to be 400 g/m^3 and the value of z determined from Equation 5.2 is 23 cm. With the same wastewater flow rate of 2,000 m^3/day, the land area of the HRAP is double of (a), or the HRAP dimensions (depth × width × length) are 0.4 × 100 × 400 m^3.

Note: to provide sufficient nutrients for algal growth, NH_4-N concentration in the wastewater needs to be increased to 40 g/m^3.

Hydraulic retention time (HRT)

The optimum HRT for HRAP should be such that most nutrients are converted into algal cells. From theoretical analysis, Oswald and Gotaas (1955) derived the following relationship:

$$HRT = \frac{C_a .h.z}{1000\ F.I_o.T_c} \qquad (5.3)$$

or

$$HRT = \frac{L_t .h.z}{1000\ F.I_o.T_c\ p} \qquad (5.4)$$

Where:

HRT = days

h = unit heat of combustion of the algae, kcal/g of algae (for sewage-grown algae = 6 kcal/g)

F = efficiency of light energy conversion to chemical energy, usually = 0.1

I_o = the amount of visible solar energy penetrating a smooth water surface, varying from 0 to 800 gcal/(cm^2-day)

T_c = temperature coefficient, values given in Table 5.2

L_t = ultimate BOD or COD of influent wastewater, mg/L

p = ratio of weight of O_2 produced and weight of algal cells synthesized, calculated from Equation 2.6 to be 1.58

The term C_a and z are as defined previously. Equation 5.4 indicates that HRT varies inversely with I_o. Therefore a strong I_o may be associated with a reduced HRT. Oswald *et al.* (1953) indicated that while other factors being constant, the most favorable environment for algal growth in continuous cultures is obtained at relatively short HRT. Under these conditions, algal growth is maintained in logarithmic phase and cells are large and fat, rich in chlorophyll, low in carbohydrate and produce protoplasm rapidly. For biological reasons the HRT should be larger than 1.8 days which is a minimum time span for generation of the algae in HRAP (Oron and Shelef 1982). Oswald *et al.* (1953) reported that the algal fraction of the SS in effluent increases with increasing HRT, and at HRT greater than 4 days, practically all of the VSS consist of algal cells. Moraine *et al.* (1979) reported that algae constituted about 30-90% of the VSS in an HRAP in Israel, and 65% being typical. They also found longer HRT to favor higher algal fraction in the HRAP water.

The maximum value for HRT of HRAP should not exceed 8 days, since under these conditions the pond will be under-loaded (lack of nutrients), causing a decrease in algae concentration. Therefore, for the maximization of the net production in HRAP, the choice of the optimum value of HRT/z (subject to environmental and biological conditions) is of utmost importance. From a practical point of view, HRT/z at a range of 6 to 12 day/m seems to be appropriate for all operational purposes (Oron and Shelef 1982).

BOD loading

BOD loading of HRAP should have an influence on algal yield because a too-high BOD loading can result in anaerobiosis and interference with the algal-bacterial symbiosis. Hsu (1970) did an experiment on HRAP in Thailand using diluted-fresh Bangkok night soil as raw material to find out the optimum design parameters of HRAP. He concluded that, for tropical region like Bangkok, the optimum pond depth, HRT and BOD_5 loading should be 0.35 m, 1.5 days, and 300 lbs/(acre-day) (336 kg/(ha-day)), respectively. Under these conditions, BOD_5 removal efficiency was about 95%, the effluent BOD_5 was below 10 mg/L, and the algal yield was around 350 lbs/(acre-day) (390 kg/(ha-day)). An experiment on a 200-m^2 HRAP by Edwards and Sinchumpasak (1981) using weak sewage (mean BOD_5 = 45 mg/L) resulted in the mean algal concentration of 94 mg/L or the mean algal yield of 157 kg/(ha-day); the organic load and HRT applied to this pond were 75 kg BOD_5/(ha-day) and 3 days, respectively.

Table 5.5 Temperature coefficients for *chlorella* grown in pilot-plant (Oswald and Gotaas 1955)

Mean temperature, in degrees		
Centigrade	Fahrenheit	Photosynthetic temperature coefficient, T_c
0	32	-
5	41	0.26
10	50	0.49
15	59	0.87
20	68	1.00
25	77	0.91
30	86	0.82
35	95	0.69
40	104	-

Mixing and recirculation

Mixing of HRAP content is essential to prevent algal sedimentation and provide interactions between the benthic deposits and free oxygen containing supernatant. Mixing keeps the nutrients in active contact with the algal cell surface, leading to a stimulation of metabolic activities and a more effective utilization of incident light (Persoone *et al.* 1980). In large-scale HRAP, mixing can prevent thermal stratification and the development of anaerobic condition at the pond bottom, and avoid photo-inhibition through a decrease of the duration of stay in over-exposed layer where irradiance might be too high for the algal cells (Soeder and Stengel 1974).

On the other hand, mixing results in the suspension of sediments and reduces light penetration. Too much mixing is also not economic for HRAP operation. Moraine *et al.* (1979) found the intensified mixing to adversely affect the algal population stability and suggests a flow velocity of algal suspension in HRAP to be 5 cm/sec. Because the surface water in HRAPs is fairly homogeneous due to paddle wheel mixing, Green and Oswald (1995) suggested that the mixing linear velocity should be maintained near 15 cm/sec due to the following reasons:

- There are two distinct biological portions in a high-rate algal pond, an oxidative bacterial floc portion and the photosynthetic algal portion. At the flow velocity of 15 cm/sec, the algal portion is suspended but the bacterial portion, being stickier and hence heavier and more flocculent, stays near the bottom where its optimal pH is about 7.0 and it is protected from the higher pH surface water. Being near the bottom, the bacterial floc does not interfere with the penetration of light into the algal portion, permitting photosynthesis to proceed.
- Maintaining a velocity of 15 cm/sec requires only 1/8 as much energy as a velocity of 30 cm/sec and only 1/64 the energy of a velocity of 60 cm/sec
- Delicate algal flocs that tend to form are not disrupted at 15 cm/sec and hence are more settleable when transferred to the settling pond.

Based on the information given above, design criteria for HRAPs are given in Table 5.5. Since the algal-bacteria symbiotic activities are greatly dependent on temperature, under tropical conditions, low HRTs and/or high organic loading rates can be employed for HRAP design and operation.

The principal advantages of pond recirculation are the maintenance of active algal and bacterial cells in the HRAP system and aeration of the influent wastewater. Most HRAP have configuration similar to that shown in Figure 5.5 in which recirculation is normally practiced in pond operation.

Although the major factors affecting HRAP performance are light intensity and temperature, the engineering parameters, which can be manipulated to produce optimum HRT in year-round operation, are pond dimensions, namely area and depth (Azov and Shelef 1982). Based on their HRAP research in Israel, they have proposed three modes of pond operation in which a comparison of estimated pond dimensions and productivity based on a community of 50,000 people is given in Figure 5.7.

Table 5.6 Design criteria for high-rate algal ponds

Pond depth (z), m	0.3-0.6
HRT, days	1.5-8
HRT/z, day/m	6-12
BOD loading, kg/(ha-day)	75-300
Mixing linear velocity, cm/sec	5-15
Channel length/width ratio	> 2

1. Constant-HRT operation, which is appropriate for tropical climates where seasonal variations in solar radiation and temperature are minimal. This method requires the least area, but also produces the least biomass.
2. Variable-HRT or -depth operation, which is recommended for moderate climates and can be economically achieved by varying pond depth at constant area using a variable-level overflow weir. During summer period when temperature is high, the required HRT and consequently pond depth should be less; and vice versa during the winter period. Azov and Shelef (1982) stated that determining the required changes in pond depth to produce optimal HRT is a matter of 'trial and error', depending on operational experiences and wastewater characteristics.

   This method of pond operation has land area requirement 25% greater than method 1, but the pond productivity is highest.
3. Variable-HRT operation using dual function ponds, which might be of interest in agricultural locations, but it has double the land requirement of method 1. The ponds are operated solely for wastewater treatment during winter, while some can be converted into fish-rearing ponds during summer.

A recent development on HRAPs by Green and Oswald (1995), called "Advanced Integrated Wastewater Pond System" (AIWPS, Figure 5.8), was found very effective in wastewater treatment and algal production. The system consists of four units in series: a primary pond (advanced facultative pond, or AFP) with internal fermentation pits, a secondary shallow continuously mixed pond (high-rate algal pond, or HRAP), a tertiary settling pond (advanced settling pond, or ASP), and a quaternary holding pond (advanced maturation pond, or AMP), which can be used as aquaculture tanks.

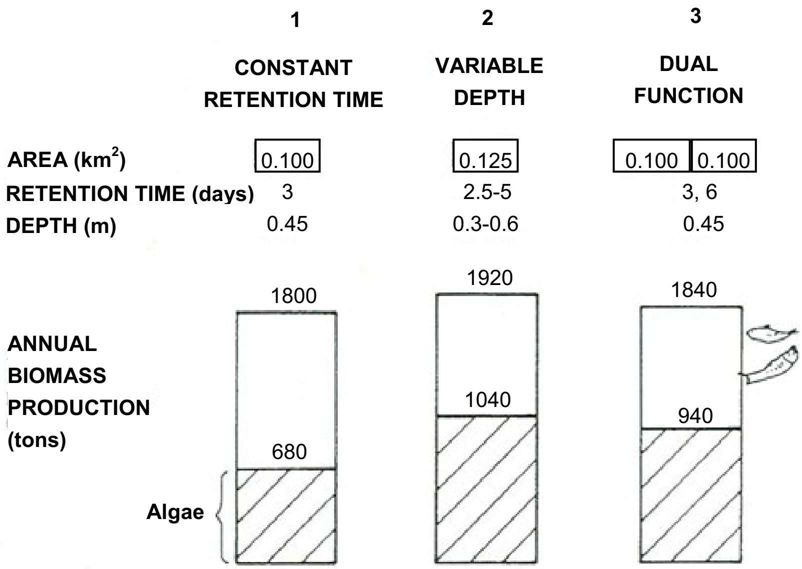

Figure 5.7. Three modes of HRAP operation.

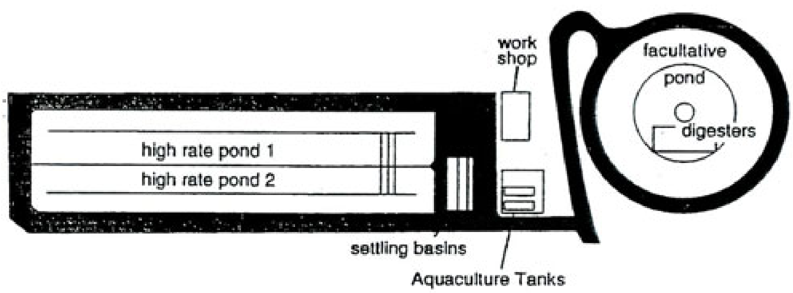

Figure 5.8 Advance integrated wastewater ponding system (Pilot plant at the University of California, Berkeley, Richmond Field Station, USA)

The AFPs are designed to retain the settleable solids in wastewater and to foster their long-term fermentation to gaseous products such as methane, carbon dioxide, and ammonia. The HRAPs are designed to produce algae and photosynthetic oxygen in sufficient, but not excessive, amounts to permit microbial oxidation of organic residuals. Algae in the HRAPs tend to raise the water pH and a pH of 9.2 for 24 hours will provide an almost 100% kill of *E. coli* and presumably most pathogenic bacteria (Oswald 1991). It is not uncommon for HRAPs to reach pH levels of 9.5 or 10 during the day, so they have a high disinfection rate. The ASPs are designed to settle and remove algal-bacterial concentrates from the oxidized waste; and the AMPs are designed to hold the treated wastewater for reuse in aquaculture or seasonal applications of irrigation water for controlled discharges and further improve the disinfection. Table 5.7 shows the performance of AIWPS. The algal biomass production ranges from 80 to 220 kg (dry weight) / (ha-day).

Table 5.7 Performance of AIWPS (Oswald 1991)

(a) St Helena, California

Parameter	Influent sewage	AFP	HRAP	ASP	AMP	% removal
HRT (days)	0	20	10	5	-	
BOD_5 (mg/L)	220	20	9	6	7	97
COD (mg/L)	440	120	70	60	30	93
Total C (mg/L)	210	140	90	70	50	77
Total N (mg/L)	40	16	13	6	4	90
Total P (mg/L)	14	13	12	8	5	64

(b) Hollister, California

Parameter	Influent sewage	AFP	HRAP	ASP	AMP[a]	% removal
HRT (days)	0	32	10	7	-	
BOD (mg/L)	194	43	7	7	-	96
TVS (mg/L)	604	393	341	347	-	42
E. coli (MPN/ 100 mL)	10^8	10^6	10^5	10^4	-	99.999

[a] Hollister's settling pond effluent is discharged to natural gravel percolation beds; there is no surface effluent

5.2.2 Estimation of algal production

A detailed literature review of photosynthetic algal yield was conducted by Goldman (1979b). He summarized that at best conversion efficiencies of less than 5% of total sunlight into algal biomass can be expected, leading to the upper limit in yields of 30-40 g (dry weight)/ (m^2-day). Although high temperature leads to high algal yields, respiratory and other decay processes are also influenced by this parameter, making temperature to be not nearly as important as sunlight in controlling algal productivity. To achieve maximum algal yield in outdoor HRAP, consideration must be given also to the factors that affect algal growth as described in section 5.2.1.

Some of the engineering models to predict algal productivity in outdoor mass culture or HRAP are given below.

Goldman formula

Based on the simple energy balance in photosynthesis and considering the characteristics of sunlight, Goldman (1979b) derived the following model in which the effect of algal decay was excluded:

$$P_a = 0.28\ I_s\ [ln\ 0.45\ I_0/I_s + 1] \tag{5.5}$$

Where

P_a = algal productivity (dry weight), g/ (m^2-day),

I_s = saturation light intensity, gcal/ (cm^2-day)

I_o is as defined in Equation 5.4.

The values I_s depends on temperature and is not the same for all cultures of algal species, but rather is a function of the physiological make-up of the particular cells in the culture. Goldman (1979b) stated that good values of I_s for different algal species from the literature generally are lacking. The data of I_s given in Table 5.7 only represent the general magnitude of I_s for different types of algae and demonstrate the effect of temperature on the I_s values or the photosynthetic efficiency factor. The range of I_s values likely to be experienced with outdoor HRAP is 29-86 gcal/ (cm^2-day) (Goldman 1979b). The value of I_o depends on the latitude and local weather conditions such as cloudy or clear sky, which can range from 0 to 800 gcal/(cm^2-day).

The effects of I_s and I_o or P_a values, based on Equation 5.5, are graphically shown in Figure 5.9. It is apparent from this figure that the algal productivity can be almost double by culturing the algal species with an I_s value of 86 gcal/(cm^2-day) instead of an I_s value of 29 gcal/(cm^2-day) at the higher light intensities (or higher I_s values). However, P_a values do not linearly increase with I_o at higher I_o values because of the light saturation effect on algal growth. The large data compilation of maximum algal yields attained in outdoor HRAP systems (Goldman 1979a) falls within the ranges shown in Figure 5.9.

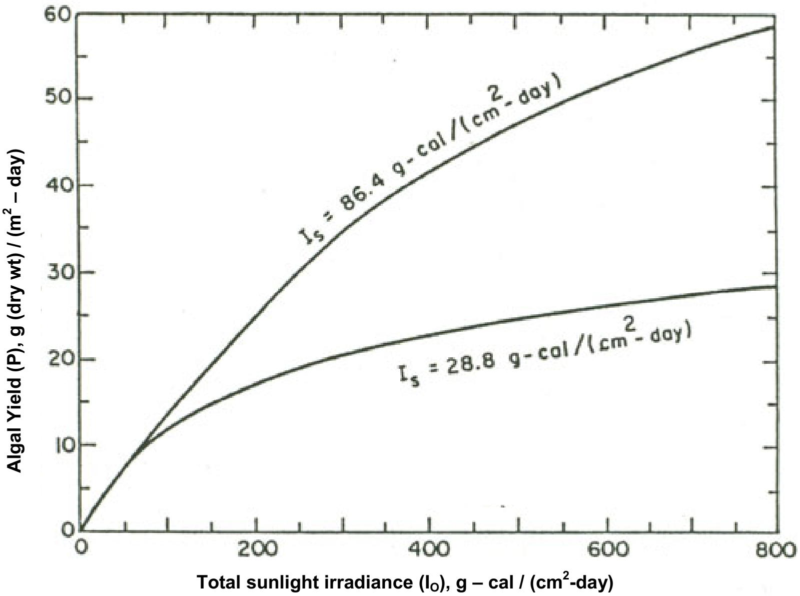

Figure 5.9 Algal yield (P_a) as a function of total solar irradiance (I_0) according to Equation 5.5 (adapted from Goldman 1979b; reproduced by permission of Pergamon Books Ltd)

Table 5.8 Summary of light saturation intensities (I_s) for different freshwater and marine micro algae (adapted from Goldman 1979b)

Species	I_s		
	Temperature (°C)	Illuminance (ft-candle)	Irradiance (gcal/(cm^2-day))
Fresh water		-	
Chlorella pyrenoidosa	25		51.8
	25	500	36
	26	-	82.1
Chlorella vulgaris	25	250	18
Scenedesmus obliquus	25	500	36
Chlamydomonas reinhardti	25	500	36
Chlorella- (7-11-05)	39	1400	100.8
Marine			
Green algae	20	500	36
Diatoms	20	1000	72
Dinoflagellates	20	2500	180
Phaeodactylum tricornutum	18	-	82.1

Oron and Shelef formula

To account for the effects of environmental and operational conditions on algal growth in HRAP, Oron and Shelef (1982) proposed the following empirical formula.

$$C_a = a.\,(HRT/z)^b\,.I_o^{\beta}\,.T^r \qquad (5.6)$$

Where,

C_a = algal concentration, mg/L
T = ambient temperature, °C
a,b,ß,r = constants, dimensionless

Units of HRT, z and I_o are days, m and gcal/(cm^2-day), respectively.

The numerical values of these constants were determined from the data collected from pilot- and field-scale HRAP operating in Israel. By applying the nonlinear least-square method, the following equation was derived:

$$C_a = 0.001475(HRT/z)^{1.71}\,I_o^{0.70}T^{1.30} \qquad (5.7)$$

The related algal productivity, P_a in g/(m^2-day) may be given by:

$$P_a = C_a\,(z/HRT) = 0.001475(HRT/z)^{0.71}\,I_o^{0.70}\,T^{1.30} \qquad (5.8)$$

An experiment was carried out in Israel with domestic wastewater (average BOD_5 of 400 mg/L) and algae such as *Micractiniumpusillum, M.quadriesetum* and *Scenedesmus dimorphus* in HRAP. Table 5.9 shows the predicted algal concentrations using Equation 5.7 and measured algal concentrations during 6 seasons. The results of this experiment show the applicability of Equation 5.7 for the assessment of algal concentration in HRAP.

Some drawbacks of Equation 5.7 are that it is applicable to influent BOD_5 ranging from 200 to 400 mg/L and to Israel conditions where these experiments were carried out. However, the same approach can be applied to suit other local conditions, but with different values of a, b, ß, r.

Theoretical estimation

Equation 2.6 implies that one mole of algal cell (molecular weight 154 g) is synthesized with production of 7.62 mole O_2. Therefore, as previously state in Equation 5.4, 1 g of algal cell is equivalent to:

Table 5.9 Environmental and operational conditions and predicted algal concentration (dry weight) of the HRAP in Israel (Oron and Shelef 1982)

	Solar radiation, I_o (gcal/(cm^2-day))	Ambient temperature (°C)	Effluent depth z, (m)	Retention time, HRT (days)	Measured algal concentration, C_a (mg/L)	Predicted algal concentration, C_a^a (mg/L)
Spring 1977	576	14.6	0.45	4	176	173
Summer 1977	679	24.2	0.45	2.9	229	215
Fall 1977	393	21.4	0.4	3.4	210	201
Winter 1977/8	318	13.8	0.45	3.9	95	101
Spring 1978	538	18.9	0.35	2.9	240	204
Summer 1979	649	25.4	0.25	2	285	321

[a] Algal concentration was predicted from Equation 5.7

$$\frac{7.62 \times 32}{154} = 1.58\text{g } O_2$$

or the factor

$$p = \frac{\text{Weight of } O_2 \text{ produced}}{\text{Weight of algal cell synthesized}} = 1.58$$

The oxygen demand of a waste is met through photosynthetic oxygen production; the ultimate biochemical oxygen demand, L_t in any time t, may be substituted for oxygen produced, and algal concentration C_a may be substituted for weight of algal cell synthesized. Therefore:

$$p = \frac{L_t}{C_a} \tag{5.9}$$

and algal productivity P_a, in g/(m^2-day) $= \frac{L_t}{p} \cdot \frac{z}{HRT}$ (5.10)

Where the units of z, HRT and L_t are m, days and mg/L, respectively.

Oswald and Gotaas (1955) reported that under environmental conditions suitable for photosynthetic oxygen production, the value of p is normally between 1.25 and 1.75. The deviation of value for p from theoretical value, 1.58, was due to various reasons. In practice, all L_t cannot be oxidized even though enough O_2 is present; therefore low value for p is observed. Or a strong wind blow can increase the surface re-aeration, increasing the value of O_2 produced; therefore high p value can be obtained.

Example 5.2

An agro-industry in Thailand is producing wastewater at a flow rate of 500 m^3/day and its COD or L_t is 400 mg/L. Determine the size of HRAP to be used to produce algae from this wastewater. The following information are given:

H	=	unit heat value of algae = 6 kcal/g
p	=	1.5
F	=	efficiency of energy conversion = 0.1
T_c	=	temperature coefficient = 0.9
I_o or I_i	=	visible solar energy irradiance = 400 gcal/(cm^2-day) or 11100 ft-candle, respectively
α	=	specific light absorption coefficient = 1.5×10^{-3}

From Equation 5.9, algal concentration in HRAP may be theoretically estimated.

$$C_a = L_t/p = 400/1.5 = 266.7 \text{ mg/L}$$

Pond depth can be estimated from Equation 5.2.

$$z = \frac{ln\, I_i}{C_a\, \alpha} = \frac{ln\, 11{,}100}{266.7(1.5\text{x}10^{-3})} = 23.3 \text{ cm}$$

Select a ‘z’ value of 25 cm.

HRT of the pond is estimated from Equation 5.3

$$\text{HRT} = \frac{C_a\,.h.z}{1000\ F.I_o.T_c.}$$

$$\text{HRT} = \frac{266.7 \times 6 \times 25}{1000 \times 0.1 \times 400 \times 0.9} = 1.11 \text{ days}$$

To satisfy the minimum time span for algal generation in HRAP and to avoid cell washout from the system, select an HRT = 1.8 days.

Volume of HRAP = flow x HRT

$= 500 \times 1.8 \quad = 900 \text{ m}^3$

Surface area of HRAP= pond volume/depth

$= 900/0.25 \quad = 3600 \text{ m}^2$

Choose 2 HRAP units, each with the following dimensions: length = 100 m, width = 18 m with 6 channels (or the width of each channel flow is 3 m).

From the above results, the value of C_a could be re-calculated using Equation 5.7 and taking T = 30°C.

$C_a \quad = 0.001475(1.8/0.25)^{1.71} (400)^{0.70} (30)^{1.30}$

= 238 mg/L which is slightly lower than the theoretical value of 266.7 mg/L as determined from Equation 5.9.

The algal productivity is determined from Equation 5.10.

$P_a \quad = C_a \text{ (z/HRT)} = 266.7 \text{ (0.25/1.8)}$

$= 37 \text{ g/(m}^2\text{-day)}$

The above P_a value is within the practical range predicted by Equation 5.5 as shown in Figure 5.9.

5.3 ALGAL HARVESTING TECHNOLOGIES

The algal biomass cultured in outdoor HRAP is mainly in the microscopic unicellular forms with concentrations in the pond water ranging from 200 to 400 mg/L. As shown in Figure 5.2, these algal cells need to be separated from the pond water prior to being used further. The HRAP effluent to be discharged to a watercourse may need to have algal cells removed so that the suspended solid content of the pond effluent is within the regulatory standard for discharge. Because of their microscopic sizes (generally less than 10 µm), the separation or harvesting of algal cells have been a major challenge and difficulty for environmental engineers and scientists to develop an efficient harvesting technology which is economically viable. Some of the technologies that have been used to separate algal cells from effluents of conventional waste stabilization ponds and HRAP systems are presented below.

5.3.1 Microstraining

Microstrainers or microscreens are low speed (upto 4 to 7 rpm) rotating drum filters operating under gravity conditions. The filtering fabrics are normally made of finely woven stainless steel and are fitted on the drum periphery. Mesh openings are normally in the range of 23 to 60 μm, but microscreens with 1 μm mesh size made of polyester fabric has been developed (Harrelson and Cravens 1982). Wastewater enters the open end of the drum and flows outward through the rotating fabric. The collected solids are continuously removed by high-pressure jets (located outside at the top of the drum) into a trough within the drum (Middlebrooks *et al.* 1974 and Metcalf and Eddy Inc. 2003). Microstrainers are normally operated at hydraulic loading rates of 5-15 $m^3/(m^2$-day), drum submergence 70-75% of height or 60-70% of filter area, and drum diameters varying from 2.5-5 m depending on the design of screen. The full-scale microstrainers with a 1 μm mesh size installed at the Camden waste stabilization ponds in South Carolina, U.S.A. (flow rate = 7200 m^3/day) were operated at hydraulic loadings between 60-120 $m^3/(m^2$-day).

Typical SS and algal removal achieved with microstrainers is about 50 percent, the range being 10 to 80 percent. Reed *et al.* (1988) suggested that microstrainers with 1 μm polyester screening media are capable of producing an effluent with BOD_5 and SS concentrations lower than 30 mg/L. However, the service life of the screen was found to be about 1.5 years, which is considerably less than the manufacturer's prediction of 5 years: this was probably due to operational and maintenance problems associated with this type of screen. A simple mesh screen with pore opening of 50 μm (Figure 5.10) can be used to separate algal cells from HRAP effluent. Although low cost in investment, algal cell removal with this method is about 50 %.

Figure 5.10 Mesh screen for separation of algal cells

Problems encountered with microstrainers having large mesh openings include inadequate solids removal and inability to handle solids fluctuations. These problems may be partially over-come by varying the speed of drum rotation. In general, drum rotation should be at the slowest rate as possible, that is, consistent with the throughput, and should provide an acceptable head differential across the fabric. The controlled variability of drum rotational speed is an important feature of the process, and the speed may be automatically increased or decreased according to the differential head best suited to the circumstances involved (Middlebrooks *et al.* 1974).

5.3.2 Paper precoated belt filtration

Because conventional microstrainer fabric (mesh sizes greater than 23 μm) is too coarse for the unicellular algae grown in HRAP and extremely fine fabric media capable of effective separation of algal cells cannot be adequately cleaned, a new harvesting process developed in Australia, utilizing a paper precoated belt filter, seems to be able to overcome these difficulties (Dodd and Anderson 1977). A schematic diagram of the paper precoated belt filtration process is shown in Figure 5.11. The belt filter incorporates a coarse fabric belt on which a precoat of paper fibres is deposited, as in a paper machine, forming a continuously renewed filter medium. The paper precoat is continuously reformed to provide a fresh filter medium having high trapping efficiency and good throughput characteristics.

According to Figure 5.11, the algal water or influent is filtered by the filtration drum. The filtered algal cells attached on the main belt are sandwiched between the main and secondary fabric belts during application of vacuum and water to separate the algae from the precoat. The paper precoat and the algal cells are then removed from the belts by water showers (no. 14 and 15 in Figure 5.11) which are called first-stage and second-stage algal concentrates. These algal concentrates are further washed to remove the algae, and the washed paper fibers are recycled to form new paper precoat.

From their experiments, Dodd and Anderson (1977) found the average SS of the first stage algal concentrate (no. 14 in Figure 5.11) to be 1.18 percent, ranging from 0.81 to 1.49 percent. The average SS of the second stage algal concentrate (no. 15 in Figure 5.11) was 0.43 percent. The second stage concentrate appeared to have flocculent characteristics, which should be beneficial in the thickening of the algal concentrate to reduce the cost of further dewatering by centrifugation or filtration.

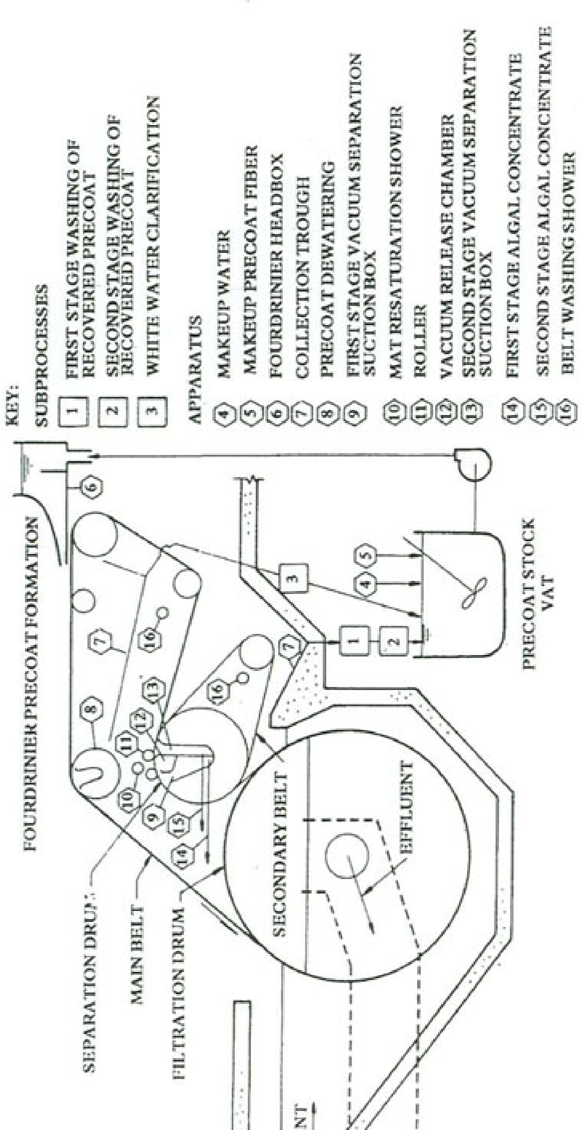

Figure 5.11 Schematic of a precoated belt filtration unit (after Dodd and Anderson 1977; reproduced by permission of Pergamon Books Ltd)

5.3.3 Flocculation and flotation

Flocculation is a process of floc formation through slow mixing so that the sizes of flocculent materials are large and heavy enough to be settled in a sedimentation tank. In water and wastewater treatment, flocculation is normally preceded by coagulation in which coagulant materials such as alum, lime, ferric chloride or polymers are added individually or in combination and rapidly mixed to enhance floc formation. Flotation is a physical process in which solid particles float to the water surface through some kinds of buoyant forces (such as dissolved-air flotation or foam flotation), and the floated particles can be skimmed off from the water surface, learning the clear liquid at the lower portion of the flotation tank. The application of coagulation process preceding flotation is expected to be beneficial to solids removal as the floated particles will be larger in size, easier to entrap or absorb air bubbles and be buoyed up by dissolved air so that they can be effectively skimmed off from the water body.

Coagulation-flocculation

Based on the above information it appears that higher efficiency of solids removal by flocculation or flotation can be achieved with the aid of coagulation. For the case of algal flocculation using alum as coagulant, the pH range between 6.0-6.8 (6.5 optimum) gave good algal removal efficiency (Golueke and Oswald 1965). The same result was also found by Batallones and McGarry (1970) when they studied jar test by using a fast mixing speed of 100 rpm for 60 sec for coagulation and a final slow mixing speed of 80 rpm for 3 min for flocculation. They found the most efficient alum dose for algal flocculation to be between 75-100 mg/L, while Golueke and Oswald (1965) found the alum dose to be 70 mg/L.

Besides alum, other polyelectrolytes or polymers can also be used as coagulant aid materials. Only cationic polyelectrolytes should be used in algal flocculation because the algal cells act like a negative charge. Batallones and McGarry (1970) found the cost of harvesting by alum alone at algal concentrations below 30 mg/L to be rather expensive and, to reduce the chemical cost, suggested the use of alum in combination with some cationic polyelectrolyte. They reported that if polyelectrolyte (Purifloc-C31) was used to aid alum, the most economic doses were 40 mg/L of alum together with 2-4 mg/L of Purifloc-C31.

It is well known that the efficiency of coagulation-flocculation is dependent on several environmental parameters such as pH, alkalinity, temperature, and turbidity, etc. Therefore laboratory or pilot-scale experiments on individual HRAP water should be conducted, wherever possible, to select the appropriate coagulant materials and other operating conditions for the coagulation-flocculation process.

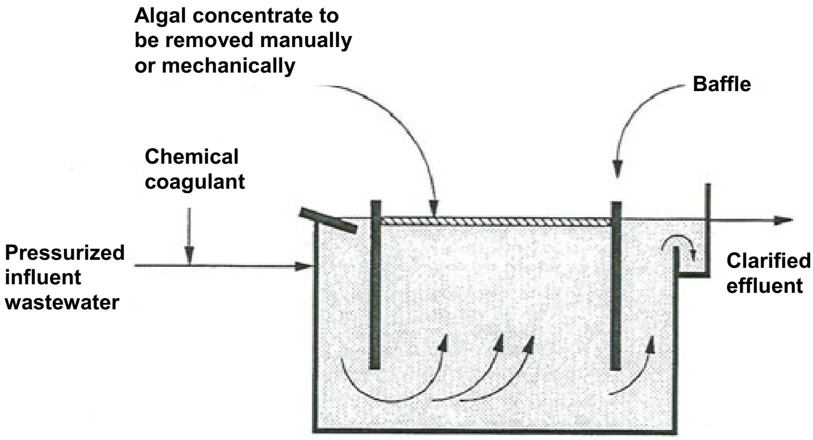

Figure 5.12 Schematic of a dissolved air flotation unit

Dissolved-air flotation (DAF)

Theoretically, there is a tendency for algal cells to float to the water surface due to the release of supersaturated oxygen gas generated during the photosynthetic period. To make the algal cells float more effectively DAF is normally employed. In DAF systems, air dissolved in the water under a pressure of several atmospheres, and the pressure is later released to the atmospheric level in the flotation tank. For small-scale operation, part or all of the influent flow is pressurized and is added with coagulant materials such as alum (Figure 5.12). For large-scale operation and to improve the system performance, the clarified effluent is normally recycled to mix with the influent feed prior to being released into the flotation tank. In this case, the recycled effluent is pressurized and semi-saturated with air, and is mixed with the unpressurized influent water. DAF efficiency depends on various factors such as the air/solids ratio, dissolved air pressure, flotation time, types and dose of coagulant aids, and pH of the water. There are various types of DAF units produced by some manufacturers in Europe and U.S.A. for full-scale application.

McGarry and Durrani (1970) conducted DAF experiments on HRAP water and found that at the alum dosages of 125-145 mg/L, pH = 5-7, air pressure = 35-50 psi gage (2.4-3.4 atmospheric pressures), and flotation time = 6-10 min, an algal concentration of 8% was obtained in the overflow effluent. Bare *et al.*

(1975) studied algal removal using dissolved-air flotation process, with and without coagulant aids. They found that at 25% recycle and 3 atmospheric recycle pressure the algal removal was 35% in batch process without coagulants. The percent removal increased to about 80 when ferric sulphate was used at 85 mg/L. The same result could be obtained when 75 mg/L of alum was used at the same operating conditions.

Autoflocculation

Autoflocculation refers to the precipitation of algae and other particulate matters in a pond when the pH rises to a highly alkaline level. This phenomenon is related to the chemical make-up of the water, and, in particular, the presence of calcium and magnesium carbonates (Middlebrooks *et al.* 1974). As the algae remove CO_2, the pH rises to a point at which precipitation of magnesium hydroxides and calcium carbonate along with algae occurs, causing removal of the particulate matters.

A recent study by Sukenik and Shelef (1984) found the proper concentrations of calcium and orthophosphate ions in the medium to be important for autoflocculation. To attain autoflocculation within the pH range of 8.5-9.0, the culture medium (or HRAP water) should contain 0.1-0.2 mM orthophosphate and between 1.0-2.5 mM calcium. Calcium phosphate precipitates are considered as the flocculating agent, which reacts with the negatively charged surface of the algae and promote aggregation and flocculation.

Removal of the precipitated algal cells require another non-agitated basin for the cells to settle, or mechanical aeration has to cease for a few hours daily if cell precipitation is to occur in the HRAP. Removal of the precipitated cells may be conducted during nighttime or early morning when the photosynthetic activity is non-existent and the algal cells do not tend to rise to the water surface.

Autoflocculation appears to be a rather simple method of algal harvesting because it does not require sophisticated mechanical equipments and operation. However its efficiency in algal removal is generally less than the aforementioned methods, and requiring a large area for construction of a settling basin. In addition a very warm and cloudless day is required to attain the high pH values (greater than 9) in HRAP water; this condition does not occur all year round in most locations.

5.3.4 Biological harvesting

The unicellular algae grown in HRAP are food for herbivorous fish (fish feeding on phytoplankton) and other macro-invertebrates. The culture of herbivorous fish in algal pond water to graze on the algae is an attractive means to produce protein biomass in the fish tissue. However, fish cannot effectively graze all the algal cells and will also discharge fish feces, causing the pond water to still contain high algal contents and organic matters. Details about fish production in wastewater can be found in Chapter 6.

5.3.5 Comparison of alternative algal harvesting methods

The literature on algal harvesting contains numerous studies and discussion of various harvesting methods (Golueke and Oswald 1965; Middlebrooks *et al.* 1974; Parker and Uhte 1975; Benemann *et al.* 1980). Besides the 4 harvesting methods listed above, there are other methods that can be used to separate algal cells such as centrifugation, fine-weave belt filtration and sand filtration. However there does not appear to be any method, which is clearly superior for a "typical" application. Due to the very wide range of conditions and objectives encountered, the selection of an algal harvesting technology and its application should be approached as a distinct case, weighing the merits/drawbacks of each method for the particular circumstances.

Factors to be considered in the selection of a harvesting method include wastewater and HRAP effluent characteristics, treatment objectives (in terms of harvested effluent quality for different water reuse applications or discharge requirements), algal product quality, capital and operating costs, energy requirements, level of operator skill required, and availability of equipments and chemicals. The specific physical properties of algae also directly affect the selection of a harvesting method, e.g. the motile euglenoids may resist sedimentation or flotation because they can swim away from the process effluent or the unicellular green algae will have sizes too small for the conventional microstrainers. It is apparent that laboratory- or pilot-scale experiments with that particular HRAP water should be conducted and the data thoroughly analyzed prior to the selection of an algal harvesting method.

5.4 UTILIZATION OF WASTE-GROWN ALGAE

Besides the benefits in wastewater treatment gained from waste-grown algae, these algae, depending on their characteristics, can be further used according to the applications shown in Figure 5.2.

5.4.1 Algae as food and feed

Protein content of algae is about 50%, which is higher than soya bean, while other vitamins and minerals are present in desirable proportions (Tables 5.10 and 5.11 show the chemical compositions of various algal species and soya bean). However Waslien (1975) reported that there is an imbalance in the amino acid composition of the algal protein, notably in the absence of sulfur-containing amino acids, methionine and cystine, making the nutritional value of algae to be considerably less than conventional foods such as eggs and milk. Another problem with the algae is their high nucleic acid content which is about 4 percent or more (see Table 5.11, the values of RNA + DNA). These nucleic acids, when being ingested in large quantity, can result in unacceptably high level of uric acid (an illness) in human blood. In addition, except the *Spirulina sp.,* most of the waste-grown algae have thick cell walls, which are not well digestible by human and non-ruminant animals (such as poultry). Therefore these cell walls have to be ruptured such as by heat or acid treatment or some mechanical means such as ball milling and crushing.

Table 5.10 Chemical composition of different algae compared with soya (% dry matter) (Becker 1981)

Component	*Scenedesmus*	*Spirulina*	*Chlorella*	Soya
Crude protein	50-55	55-65	40-55	35-40
Lipids	8-12	2-6	10-15	15-20
Carbohydrates	10-15	10-15	10-15	20-35
Crude fibre	5-12	1-4	5-10	3-5
Ash	8-12	5-12	5-10	4-5
Moisture	5-10	5-10	5-10	7-10

Table 5.11 Chemical composition of algae (g/100 g dry matter) (Becker 1981)

Component	*Spirulina*	*Scenedesmus*
Total nitrogen	11.0	8.3
Non-protein nitrogen	1.5	1.05
Protein-nitrogen	9.5	7.25
Available lysine (g/100 g protein)	2.96	3.66
Ribonucleic acid (RNA)	2.90	4.4
Deoxy-ribonucleic acid (DNA)	1.00	1.6
Calcium	0.75	0.85
Phosphorus	1.42	1.9

The thin-walled algae, such as *Spirulina*, thus appear to be a suitable algae species that should be cultured for use as human food supplement. However, as pointed out by Goldman (1979a), it is rather impossible to control algal speciation in outdoor cultures for sustained periods, except in unique chemical environments that rarely exist in nature. Due to the rapid generation of algae, certain species tend to dominate through natural selection regardless of which algae is used as an inoculum. Invariably, the thick-walled and multicellular freshwater species such as *Chlorella, Scenedesmus* and *Micractinium* tend to become dominant over time (Goldman 1979b).

The direct use of algae for human food supplement may be unnecessary, if the algae can be fed to the animals (pigs, poultry, and fish, etc.) and these animals are used as food for human. Hintz *et al.* (1966) reported that the waste-grown algae (*Chlorella* and *Scenedesmus*) were 73 percent digestible when fed to ruminant animals such as cattle and sheep, and were only 54 percent digestible when fed to pigs. The digestible energy content for the ruminants was 2.6 kcal per g algae. These algae were found to supply adequate protein to supplement barley for pigs. Alfafa-algae pellets, when fed to lambs, resulted in higher weight gains than alfafa pellets alone.

Algae are basically not palatable to most of the livestocks, but this may be overcome by pelletizing the processed algae with usual feed of particular animal, such as steam barley in the case of cattle. In general, the waste-grown algae appear to have potential as a livestock feed because of the high contents of protein and other valuable substances (Tables 5.10 and 5.11).

Edwards *et al.* (1981a) reported the use of waste-grown algae as feed for herbivorous fish (Tilapia). Extrapolated fish yields approaching 20 tons/(ha-year) were obtained in the 4m^3 concrete pond system based on 3 month growing periods under ambient, tropical conditions. A linear relationship was established between fish yields and means algal concentration in the fish ponds, in which an algal concentration of 70 mg/L in the pond water was considered to be high enough to produce good fish growth. Higher algal concentrations were not recommended since it might lead to zero dissolved oxygen concentrations in the early morning hours.

5.4.2 Algae for fertilizer

Algae may be used directly or indirectly as fertilizer in agriculture. In direct use, algae is cultured in HRAP and then irrigated to crops. This method is simpler, but requires more time because the algal cells need to be decomposed in the soil first. In term of indirect use, algae is harvested and composted and then applied to soil as fertilizer. The application of algal-laden water to crops should be undertaken with due respect to public health considerations and guidelines as proposed in Table 2.27.

Since algae are capable of fixing nitrogen from atmosphere, they have an important role in agriculture. It was reported that rice field inoculated with the nitrogen fixing algae *Tolypothrix tenvis* for four years produced 128% more crop than uninoculated field. Furthermore, the plant from the inoculated field contained 8.4 kg N/ha more than the uninoculated field. Also, using algae as fertilizer will improve the soils' water holding capacity which is an advantage to crop yield (Alexopulos and Bold 1967).

5.4.3 Algae for energy

The fuel characteristics of dry algae (average heat content of 6 kcal/g) are similar to those of medium-grade bituminous coal, and suitable for using as energy source (Benemann *et al.* 1980). Algae can be used together with other organic amendments to produce biogas from anaerobic digestion.

5.4.4 Algae as source of chemicals

A significant amount of lipids is present in algal cells (Table 5.12), which can be used for many industrial purposes such as manufacturing of surfactants, grease, textiles, food additives, cosmetics and pharmaceuticals. The lipids of micro algae often contain large amount of neutral lipids, mainly as glycerides, and this might serve as a source of glycerol (Aaronson *et al.* 1980).

Micro algae may also serve as a source of steroids. The concentration of steroids in algae is variable but significant amount may be found in some algae. Algae may also contain upto 0.2% of dry weight as carotenoids (Paoletti *et al.* 1976). Some medicinal products have been isolated from algae (Volesky *et al.* 1970).

5.4.5 Algae as a future life support technology

As shown in Figure 1.1 and Table 1.2, the increase in population growth and decrease in arable land will require technologies of food or protein production which are cost-effective and use less land area. The HRAP technology as described in this chapter should be able to respond effectively to this need and the algal cells can be used at least as fish and other animal feeds. The current progress in space exploration should eventually lead to a possibility that human beings can stay in space, on the Moon or Mars for a longer period of time and the algal technology that produces O_2 and algal protein biomass is being considered as a potential life-support technology.

Table 5.12 Total lipids in algae harvested from high rate algal ponds in Israel (Aaronson *et al.* 1980)

Major species	Total lipids (% of dry weight)	Neutral lipids (% of dry weight)
Chlorella	22.6	10.9
Euglena	11.0	8.9
Micractinium	17.4	6.0
Oocystis	19.9	13.5
Scenedesmus	22.2	10.4

5.5 PUBLIC HEALTH ASPECTS AND PUBLIC ACCEPTANCE

5.5.1 Public health risks

Production of waste-grown algae involves some public health risks due to:

- Contamination of the pathogens normally presents in raw wastes, and
- Accumulation of heavy metals and other toxic compounds in algae cells.

As discussed in section 5.1, pathogen die-off in the algal ponds can take place due to the ultra-violet light, algal toxins produced by algae cells, competition with other micro organisms, inhibitory environments such as high pH during photosynthesis, and sedimentation with sludge. However, a complete removal of pathogens never exists in practice, because they may be protected by self-shading of algae and clumping with sewage solids.

Edwards *et al.* (1981b) found the microorganism removal in their HRAP unit located in Thailand to be about 1 order of magnitude. The ranges of bacterial densities in the HRAP effluents were 1.0×10^5 - 1.3×10^{10}, 1.6×10^5 - 2.4×10^6, and 7.0×10^4 - 9.2×10^5 no./100 mL for the standard plate count bacteria, total coliforms and fecal coliforms, respectively. According to Table 2.27, this HRAP effluent is not suitable for unrestricted irrigation (e.g. irrigation of edible crops), but may be used for restricted irrigation such as irrigation of trees and other industrial crops.

Care should be taken on occupational risks to the people working with HRAP units. The possibility of contamination to these people is high, particularly during algal harvesting which may lead to the spreading of pathogens to other people by carrying with body or clothes. The possibility of swallowing pathogens during the working period cannot be ruled out. Therefore it is always advisable to use protecting covers, such as masks, hand gloves, etc., when working in algal pond system.

The possibility of algal contamination with toxic substances and heavy metals has also another adverse effect on public health. Heavy metals and pesticides may be concentrated in algae by the process of bioaccumulation, inducing impact on other consumers in food chain through biomagnification (as discussed in section 2.5). The concentration of toxic substances in algae is expected to be higher than in wastewater discharged into the pond. Therefore, to avoid such risks, the treatment of wastewater up to the allowable concentration of heavy metals and other toxic substances should be done prior to the feeding of this wastewater to HRAP. The waste-grown algae to be used for human or animal feed should be regularly monitored for the presence and concentrations of these substances.

5.5.2 Public acceptance

Unprocessed freshwater algae tend to have strong smell and taste similar to those detected in natural waters that are undergoing eutrophication. Algal texture is also slimy and uninviting, making the direct dietary use unlikely for human and animals (except for herbivorous fish). Therefore the conversion of algal biomass into dietically acceptable forms or palatable material (such as the pelletization) is important, and some encouraging results on the use of pelletized algae as animal feed have been reported (section 5.4).

Considering the results on the acceptability and the nutritive value of waste-grown algae, the prospect of their direct use as human protein supplement is relatively remote. Although the strain *Spirulina* seems to have potential to be used as human or animal feed, the main problem is that, whereas species control is relatively simple with terrestrial crops so that the best suited species are grown, it is almost impossible to control algal speciation in outdoor HRAP cultures (Goldman 1979a). The uses of HRAP and the waste-grown algae appear to be limited to solving specific environmental problems such as wastewater treatment and other applications shown in Figure 5.2. These limitations include the upper limit in algal yield of 30-40 g/(m^2-day), the economics of algal harvesting and the algal cell characteristics, which are the key factors in determining the application of HRAP to a particular situation.

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5.7 EXERCISES

5.1 There are three formulas presented in this book for estimating algal productivity in high-rate algal ponds (HRAPs): the Goldman formula (Equation 5.5), the Oron and Shelef formula (Equation 5.8) and theoretical estimation (Equation 5.10). Discuss the merits and shortcomings of these formulas.

5.2 You are to obtain the meteorological data (for the past 12 months) which are important for algal production in high-rate algal ponds from the local weather bureau. Using these data and those reported in Chapter 2, determine the amount of algal cells that can be produced if all of your city's wastewater is to be used as the influent feed. Use the three formulas in section 5.2.2 for the calculation and discuss which of the three calculated results of algal production is most applicable to your city.

5.3 You are to survey the algal harvesting equipments currently available in the market in your country or elsewhere. Based on your inspection and information obtained from the equipment manufacturers, describe the equipment that appears most impressive with respect to: the harvesting technique employed, efficiency of algal harvesting, costs of investment and operation and maintenance.

5.4 If human beings are to live in space or on the moon for an extended period of time, discuss the possibility of producing oxygen and algal single-cell protein from the wastes we produce. Estimate the amount of oxygen and algal protein that can be produced from a person's wastes using the data given in Chapter 2. Also sketch the bioreactor(s) to be constructed in a space shuttle and/or the moon to recycle the human wastes.

5.5 A food-processing factory produces 400 m^3/day of wastewater with an average COD concentration of 400 mg/L. The factory wants to construct its own high-rate algal pond (HRAP) to produce algal single cell protein from this wastewater. As a consulting engineer, you are asked to estimate the land area required and the annual algal production including the income that can be earned from the sale of the algal biomass. Submit the schematic drawings of the HRAP. The following information is given:

HRT for HRAP = 2-5 days
Depth of HRAP = 0.2-0.4 m.
Average I_0 = 400 gcal/ (cm^2-day).
Mean temperature = 25°C
Light saturation intensity (I_s) is to be estimated from Table 5.7.
Cost of algal harvesting = US$ 0.2/m^3 of algal water
Algal density in HRAP = 300 mg/L
Price of algae = US$ 30/kg (dry weight)

5.6 A small community has a one-ha land available to treat its sewage with a COD of 300 mg/L. It plans to build high rate algal ponds (HRAPs) on this piece of land to treat the sewage. Determine the total treatment capacity of the HRAPs and the optimum pond depth. Also estimate the daily algal and protein production to be obtained from this piece of land. Additional information is given below:

I_0 or I_i = visible solar energy irradiance = 500 gcal/(cm^2-day) or 13,900 ft-candle
α = specific light absorption coefficient = 1.5x10^{-3}
T_c = temperature coefficient = 0.8
F = efficiency of energy conversion = 0.1
p = 1.6
h = unit heat of algae = 6 kcal/g

5.7 A municipality in Vietnam produces wastewater with the following characteristics:

Flow rate = 2000 m^3/day
BOD_5 = 100 g/m^3
NH_4-N = 20 g/m^3

a) If this wastewater is to be treated in a high-rate algal pond (HRAP) to produce algal density of 200 g/m^3, determine the dimension (depth × width × length) of the HRAP to achieve this objective. Draw schematic diagram of this HRAP.

The following information about HRAP are given in Equation 5.2.

$$z = \frac{\mathit{ln}\, I_i}{C_a . \alpha}$$

Where,

z = depth of HRAP, cm

I_i = measured light intensity = 10,000 ft-candle

C_a = algae density, mg/L

α = specific light absorption coefficient= $1\text{x}10^{-3}$

Hydraulic retention time of HRAP = 5 days

b) If we want to increase the algal productivity of this HRAP to be twice of that given in (a), suggest methods to achieve this objective and the required dimension of the HRAP. Also suggest methods to re-use the produced algal cells that would be acceptable to the public.

6

Fish, chitin, and chitosan production

Among several waste recycling methods, the reuse of human and animal wastes for the production of algae and fish has been extensively investigated. Although the algal cells photosynthetically produced during sewage treatment contain about 50% protein, their small sizes, generally less than 10 μm, have caused some difficulties for the available harvesting techniques, which as yet are not economically viable (see Chapter 5). Apart from aesthetic reasons, one of the drawbacks concerning the direct utilization of the waste-grown algae as an animal feed, except *Spirulina*, has been the low digestibility of the algal cell walls. Thus the culture of phytoplankton-feeding (herbivorous) fish in the same pond to graze on the algae, or feeding the algal-laden water to herbivorous-fish ponds is attractive, in order to produce the fish protein biomass which is easily harvestable for animal (or human) feed.

There are basically three techniques for reusing organic wastes in aquaculture: by fertilization of fish ponds with excreta, sludge or manure; by rearing fish in effluent-fertilized fish ponds; and by rearing fish directly in waste stabilization ponds (such as in maturation ponds). A World Bank report (Edwards 1985) cited several Asian countries, especially China, where excreta or animal manure is fed to fish ponds for the purpose of fish production. Most fish farmers also add supplementary feed such as agricultural by-products and grains to the fish ponds.

The second and third techniques of waste reuse in aquaculture have been practiced in both developing and developed countries. There are about 2,500 ha of sewage-fertilized fish ponds in Calcutta, India; 270 ha in Hunan, China; 233 ha in Munich, Germany; 50-100 ha in Israel; and a smaller-scale operation in Hungary. When properly operated, the productivity of fish ponds using wastewater has been found to be higher than that of inorganically fertilized ponds (Allen and Hepher 1976).

Some reported yields of fish raised in waste-fed ponds in various countries are shown in Table 6.1.

Another type of aquacultural waste that has high reuse potentials is shrimp biowaste. Shrimp production is being done in several tropical countries such as Thailand, Vietnam, Indonesia, India, China and Honduras. Thailand is currently one of the largest shrimp producers with an estimated shrimp production in 2006 of 450,000 tons, about 10% of the total world production. The shrimp biowaste, which is mostly shrimp shells, comprises about 40% of the total shrimp production. Since shrimp shells contain about 10-20% chitin, the production of chitin and chitosan from shrimp shells, as earlier stated in section 1.2.3, would bring economic returns and reduce pollution load resulting from the disposal of shrimp biowaste to landfills.

The cultivation of fish in waste-fed ponds and production of chitin and chitosan will be described in this chapter.

6.1 OBJECTIVES, BENEFITS AND LIMITATIONS OF FISH CULTIVATION IN WASTE-FED PONDS

The main objectives and benefits that can be gained from waste recycling through fish production are as follows:

6.1.1 Waste stabilization and nutrient recycling

Waste treatment is the primary objective of any waste recycling scheme and the inclusion of fish production recovers nutrients in the waste, such as N, P and K. Addition of waste or its by-products such as biogas slurry and compost to fish pond resulted in increased fish yields (Polprasert *et al.* 1982). Due to the economic value of fish, part of the waste treatment costs can be recovered. This financial return will be an incentive for safe disposal of waste, which will lead to better public health conditions, particularly among the rural people where malnutrition and excreta-related diseases are common.

Table 6.1 Fish yields in waste-fed ponds

Country	Types of waste	Yield	Remarks	References
Israel	Cattle manure	10,950 kg/(ha-day)	Extrapolated from experiments	Schroeder (1977)
	Duck manure and waste duck food	14,600 kg/(ha-day)		Wohlfarth and Schroeder (1979)
Philippines	Biogas slurry	8,000 kg/(ha-day)	Extrapolation	Maramba (1978)
Indonesia	Live stock waste	7,500 kg/(ha-day)		Djajadiredja and Jangkaru (1978)
Poland	Sugar beet waste	400-500 kg/(ha-growing season)		Thorslund (1971)
Taiwan	Nightsoil	6,893-7,786 kg/(ha-year)		Tang (1970)
Calcutta, India	Wastewater	958-1,373 kg/(ha-year)	Indian Carp	Edwards (1985)
China	Wastewater	6,000-10,000 kg/(ha-growing season)		Edwards (1985)
Munich, Germany	Wastewater, loadings = 30-77 kg BOD_5 /(ha-day)	500 kg/(ha-growing season)	Common Carp	Edwards (1985)
Hungary	Wastewater	1,700 kg/(ha-growing season)	Poly culture, Chinese carp and common carp	Edwards (1985)
U.S.A	Wastewater effluent, 37 %	126-218 kg/(ha-year)	Channel catfish	Colt *et al* (1975)
	Wastewater	5000 kg/(ha-year)	Silver carp, big head carp	Henderson (1983)
Asian Institute of Technology, Thailand	Septage, loading = 150 kg/COD/(ha-day)	5,000-6,000 kg/(ha-year)	Tilapia (extrapolation)	Edwards *et al* (1984)
	Biogas slurry, loading =100 kg COD/(ha-day)	3,700 kg/(ha-year)	Tilapia (extrapolation)	Edwards *et al* (1988)

6.1.2 Upgrading effluent from waste stabilization ponds

Algae in suspension increase the suspended solids content of most waste stabilization pond effluents. (Waste stabilization ponds are a waste treatment process encompassing reactions of the algal-bacteria symbiosis as described in Chapters 2 and 5) Effluent discharge without the removal of algae might cause algal blooms or increasing organic and nutrient loads to the receiving waters. Introducing fish ponds in series with waste stabilization ponds or its rearing in the waste stabilization ponds was found to reduce the algal and bacterial concentrations to a considerable extent when herbivorous fish species (Tilapia and silver carp) were used (Schroeder 1975). The layouts in Figure 6.1 could be used for the above purpose. In this way, the death of fish in the fish ponds may also indicate the presence of some toxic materials and/or low dissolved oxygen (DO) levels in the effluent discharging into the receiving water.

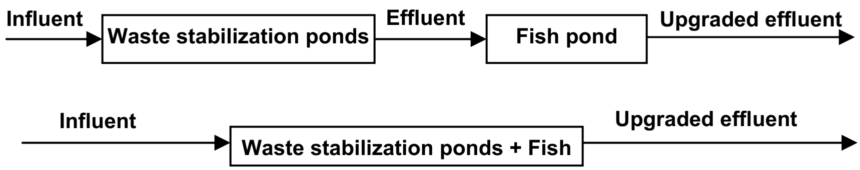


Figure 6.1 Layouts to upgrade waste stabilization pond (WSP) effluents using fish

6.1.3 Better food conversion ratio

Fish are cold-blooded animals and, unlike other farm animals such as cattle or poultry, do not have to spend a lot of energy for movement because friction is less in water. Thus fish have a better food conversion ration than any other farm animals. Table 6.2 compares the relative growth and feed utilization of farm animals and fish during a period of rapid growth. Food conversion ratio (FCR) is defined as:

$$\text{FCR} = \frac{\text{Dry weight of feed given (kg)}}{\text{Wet weight of animal gained (kg)}}$$

therefore, the lower the FCR, the better the food conversion efficiency.

6.1.4 Operational skill and maintenance

Fish culture does not require highly skilled manpower for its operation. Fish harvesting is easier than algal harvesting. Fish processing is usually not required for human consumption. For other uses such as animal feeds, drying is generally sufficient.

However, fish production from wastes might have some or all of the following limitations:

Land requirement and existence of a waste collection system

Land requirement for fish production is quite large as the organic loading to fish ponds has to be low to avoid DO depletion at dawn. Land should be available at low cost and closer to the source of waste and natural water courses (e.g. canals or rivers). The transportation of waste should be safe, easy and cheap. If the waste is available in a concentrated form such as septage, suitable sources of water to make-up the evaporation and seepage losses should be available.

Table 6.2 Efficiency of feed utilization of various animal species per 1000 g of feed intake (adapted from Hastings and Dickie 1972)

Species	Live weight gain (g)	Food conversion ratio	Energy gain (kcal)	Protein gain (g)
Chicks	356	2.8	782	101
Pigs	292	3.4	1492	30
Sheep	185	5.4	832	22
Steers	163	6.1	748	26
Channel catfish	715	1.4	935	118
Brown trout	576	1.7	608	75

Availability of suitable fish fry

Fish species suitable for stocking in waste-fed ponds should be available locally at low price. If such facility for fish fry production is not available or its production is not economically feasible locally, fish production is not possible.

Public health risks

Waste-grown fish have a potential to be contaminated with several kinds of pathogens that may be present in the waste itself (Table 2.23). Fish growing in a medium that has high concentrations of heavy metals or other toxic substances may, through the processes of bioaccumulation and biomagnifications, contain high concentrations of these substances in the fish tissue.

Marketing and public acceptance

Unless the public is convinced that waste-grown fish are safe for consumption, the fish production is bound to fail. In those areas where fish from sea or river origins are available in sufficient quantity and cheap, marketing of waste-grown fish will be difficult for human consumption. However, other methods of use (i.e. as animal feed) or other recycling options have to be considered.

6.2 HERBIVORES, CARNIVORES AND OMNIVORES

Feeding is one of the most essential factors that strongly influence the growth rate of fish. Moreover, similar to other animals, different fish species have their own special feeding habits. Fish can be classified into three groups on the basis of feeding habits. Their morphologies are also different accordingly, mainly in the aspect of the specialized type of alimentary system. Thus, the functional morphology of fish species can often indicate the type of food they eat and those they are unable to eat. These three groups are characterized below:

6.2.1 Herbivorous fish

Herbivorous fish lack teeth, but possess fine gill rakers that can sieve microscopic plant from the water; they also lack a true stomach (i.e. a highly muscular, acid secreting) but possess a long, thin-walled intestine. They mainly feed on plant including algae and higher plants. Typical examples are grass carp (*Ctenopharyngodon idella*) (unlike other herbivores, its gut is very short), and silver carp (*Hypophthalmichthys molitrix*) (Figure 6.2 a, b).

Under optimum conditions, small grass carp, less than 1.2 kg, may eat several times their body weight of plant material daily (NAS 1976). Thus, in addition to being as a source of protein, many herbivorous species, such as grass carp and silver carp, are often grown in the weed-infested water for biological control of phytoplankton blooms and some aquatic weeds.

6.2.2 Carnivorous fish

Carnivorous fish have teeth well developed to seize, hold and tear, and gill-rakers modified to grasp, retain, rasp and crush prey. There is a true flask-like stomach and a short intestine, elastic and thick walled. These fish mainly eat zooplankton, insects, bacteria, trash fish and other animals. Snakehead (*Ophicephalus striatus*) (Figure 6.2c) is mainly carnivorous, feeding on small fish, crustacean, insects and worms. Usually carnivorous fish are preferred to other fish by people for their high nutritive value and taste. But much higher investment is needed for carnivores' feed and fertilizer than other fish.

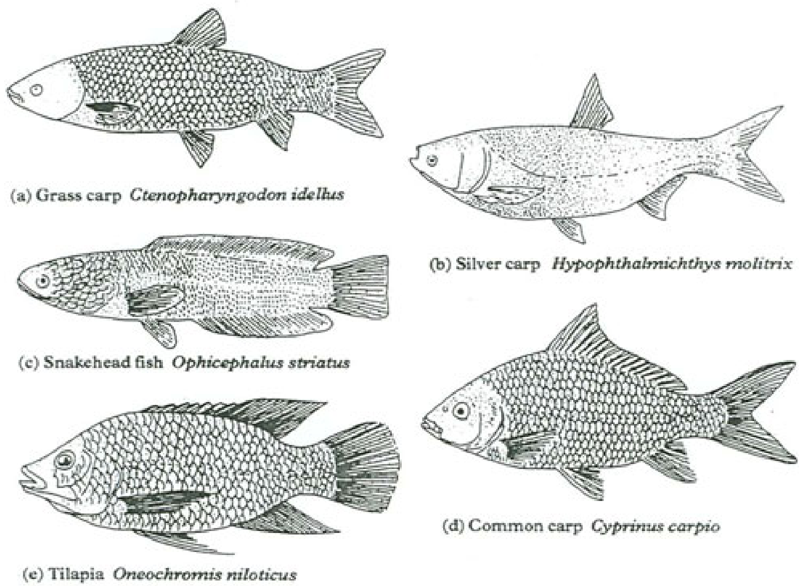


Figure 6.2 Examples of herbivores, carnivores and omnivores

6.2.3 Omnivorous fish

Carnivorous fish have alimentary systems, which are more or less intermediate between those of the extreme herbivores and carnivores, but there is a range of types between the extremes. The alimentary canal is much longer, relative to body length. Most fish belonging to these groups, that consume both animal and plants, for example, the Chinese common carp (*Cyprinus carpio*) and Tilapia (*Oreochromis niloticus*) (Figure 6.2d & e), have a wide range of diet.

The terms herbivores and carnivores have relative meaning. Usually they just indicate the type of food predominantly consumed by the fish (actually most fish are highly adaptable in their feeding habits and utilize the most readily available foods (Lagler *et al.* 1962)). Relatively few kinds are being strict herbivores or carnivores, and perhaps none of all feed solely on one organism. Food habits may change as fish grow, accompanied by marked change in the morphology of alimentary system in early life. Fish such as Bermuda angelfish (*Holacanthus bermudensis*) may even change their diet with season. It may be quite herbivorous in winter and spring and become predominantly carnivorous in the summer and early fall.

Therefore, feeding materials will vary with the different fish species and the stages of development according to their feeding habits, so that fish can keep growing at higher rate.

Fish to be reared in waste-fed ponds should have the following characteristics:

- tolerant to low DO level which can occur during night time or at dawn when photosynthetic oxygen production does not occur,
- herbivorous or omnivorous in nature to feed on the waste-grown phytoplankton, and
- tolerant to diseases and other adverse environmental conditions.

Some species such as Tilapia (Figure 6.2 e), Chinese carp, and Indian carp have been widely used in waste recycling practices. Organic wastes, including septage, could provide sufficient nutrients to promote the growth of phytoplankton and consequently of zooplankton which is natural food of these fish (Polprasert *et al.* 1984). Among these species, Tilapia needs to be particularly mentioned, for its being used widely in waste recycling in the tropical and sub-tropical areas. It feeds directly on algae and other primary aquatic vegetation (and on zooplankton as well). It grows rapidly and multiplies abundantly. Furthermore, it has better tolerance to low DO level and resistance to diseases (which often occur in fish ponds) than many other species such as carp.

The culture of carnivores is also of interest in waste recycling if fish for human consumption is desired. But they have to be raised in separate ponds fed with pellets made from herbivores, omnivores, or trash fish (to allow the growth of herbivores or omnivores), and to safeguard public health because the carnivores will not be in direct contact with the organic wastes. Catfish, snakehead and shrimp, which are of high market value, are the carnivores commonly reared.

6.3 BIOLOGICAL FOOD CHAINS IN WASTE-FED PONDS

Food chain is the series of organisms existing in any natural community through which energy is being transferred. Each link in such a chain feeds on and obtains energy from the ones preceding it. In a pond ecosystem, there are generally three major groups of organisms present in the food chain, similar to the other marine and freshwater ecosystems. The three groups consist of: the primary producers; the primary, secondary and tertiary consumers; and the decomposer organisms (Figure 6.3).

At the beginning of the food chain, the primary producers (algae and aquatic plants) represent the first trophic or energy level. They synthesize organic materials (or cell biomass) through photosynthesis (e.g. Equation 2.6), utilizing the nutrients present in the water and light energy. Next is the primary consumer group, mainly zooplanktons and the herbivores, which consumes the primary producers, then they are preys for secondary consumers such as small fish and other plankton feeders. In this step, some fish consume benthic animals that grow at the pond bottom. Some herbivorous fish such as silver carp consumes phytoplankton directly and it can also take detritus. Tertiary consumers such as snakehead predate small fish. Depending on the type of fish stocked, they feed on phytoplankton or zooplankton and are primary consumers, secondary consumers or tertiary consumers.

The waste material produced by fish and decaying biomass will settle to the pond bottom and be decomposed by bacteria (the decomposers), resulting in the release of nutrients such as CO_2 and NH_3 (Equation 2.1) required for the primary production.

When comparing food chains in a normal fish pond and a waste-fed fish pond, there are no wide differences between them. However, to allow the herbivorous fish to grow effectively and maximizing the fish biomass production, carnivorous fish (tertiary consumers) are not normally stocked in the waste-fed fish ponds where herbivores are being reared. Additionally, in waste-fed fish ponds, there are more nutrients for primary producers due to the application of waste and its decomposition. Food chain depends on the primary productivity of the pond, which in turn depends on the nutrients and light. The subject of environmental requirements in waste-fed ponds will be discussed in section 6.5.

Another important consideration related to food chain is the problems caused by biomagnification and bioaccumulation. Biomagnification may be defined as the accumulation of toxic materials such as pesticides or heavy metals in an organism in any particular trophic level at a concentration greater than that in its food or the preceding trophic level so that essentially animals at the top of food chain accumulate the largest residues (see Figure 6.3). Bioaccumulation is the phenomena where the toxic matter is in equilibrium at a higher concentration in tissues than that of the surrounding aquatic environment. This depends on the time of exposure, rate of uptake, metabolism within organism, rate of excretion, potential for storage in tissues and the physiological state of organism. Therefore the effect of both factors should be investigated especially when industrial or agricultural wastes containing high concentrations of heavy metals and/or toxic organic compounds are to be applied to fish ponds.

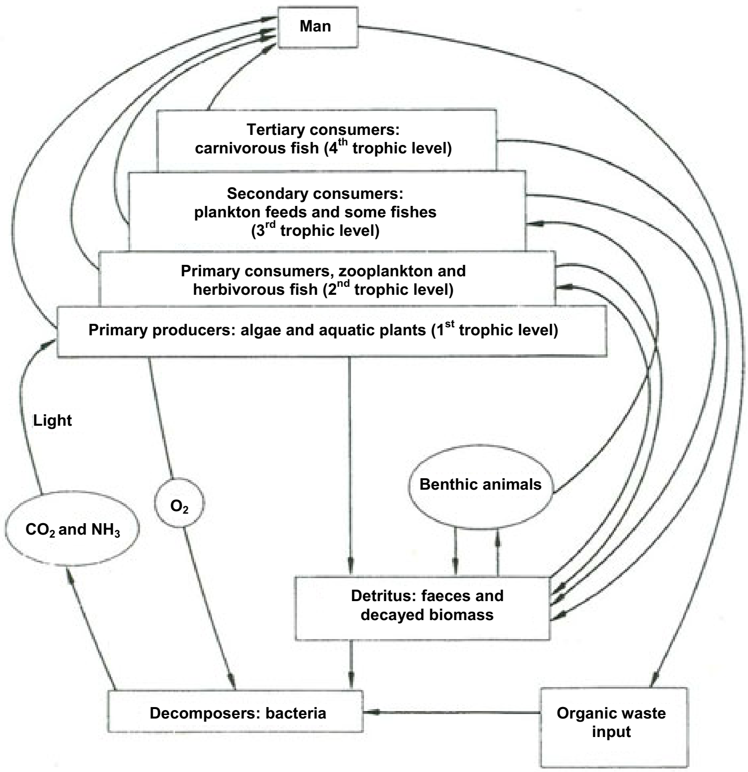


Figure 6.3 Food chain and other relationships in waste-fed ponds

A well-known example of bioaccumulation and biomagnifications involves the pesticide DDT, which is now banned in the United States (Campbell 1990). DDT concentration in a long Island Sound food chain was magnified by a factor of about 10 million, from just 0.000003 ppm as a pollutant in the seawater to a concentration of 25 ppm in a fish-eating bird, the osprey (see Figure 6.4).

6.4 BIOCHEMICAL REACTIONS IN WASTE-FED PONDS

In a waste-fed fish pond that is functioning well, algae, bacteria and fish are having symbiotic relationships. The oxygen and food for fish are to be produced by the algae, while bacteria decompose the waste. Figure 6.5 depicts the interactions among these organisms in a pond fed with wastewater or sludge.

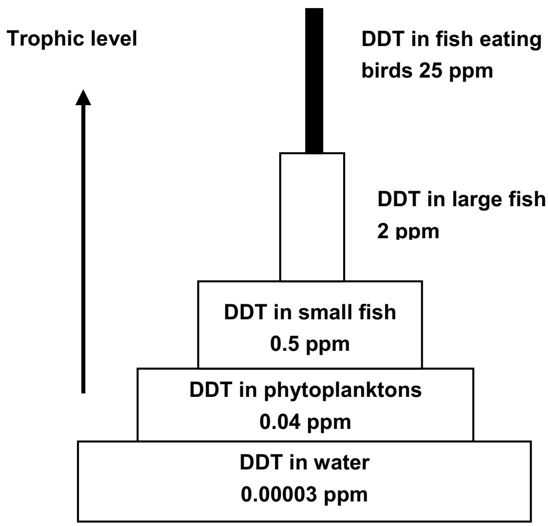


Figure 6.4 Bioaccumulation and biomagnifications of DDT in a food chain (adapted from Campbell 1990)

The biochemical reactions occurring in waste-fed fish ponds should be similar to those of facultative waste stabilization ponds in which the organic matter is decomposed by a combination of aerobic, facultative and anaerobic bacteria. Three zones exist in the ponds: the first is an aerobic zone where aerobic bacteria and algae exist in a symbiotic reaction, i.e. the oxygen supplied partly by natural surface re-aeration and from algal photosynthesis (Equation 2.6) is used by the bacteria in the aerobic decomposition of the organic matter (Equations 2.1 and 2.2); the nutrients and carbon dioxide released in this decomposition are, in turn, used by the algae (Equation 2.7). The second is an intermediate (facultative) zone which is partly aerobic and partly anaerobic, in which waste stabilization is carried out by facultative bacteria; and the third, an anaerobic bottom zone in which the accumulated solids are decomposed by anaerobic bacteria. Fish normally live in the aerobic and facultative zones where oxygen and food (algae) are present.

When organic wastes are discharged into a pond, the soluble and colloidal compounds that remain in suspension will be decomposed by the aerobic and facultative bacteria. The settleable solids will settle down to the pond bottom and, together with other decayed biomass that settles there, forming a sludge layer. Anaerobic reactions occurring in the sludge layer zone are similar to those described in Chapter 4 in which there will be releases of soluble organic by-products (such as amino acids and volatile fatty acids, etc.) and gaseous by-products such as CH_4 and CO_2. Since the pond depth is usually about 1 m, these soluble by-products will dissolve in the water due to wind-induced mixing and fish movement, which will be further decomposed by the aerobic and facultative bacteria present in the above pond layers.

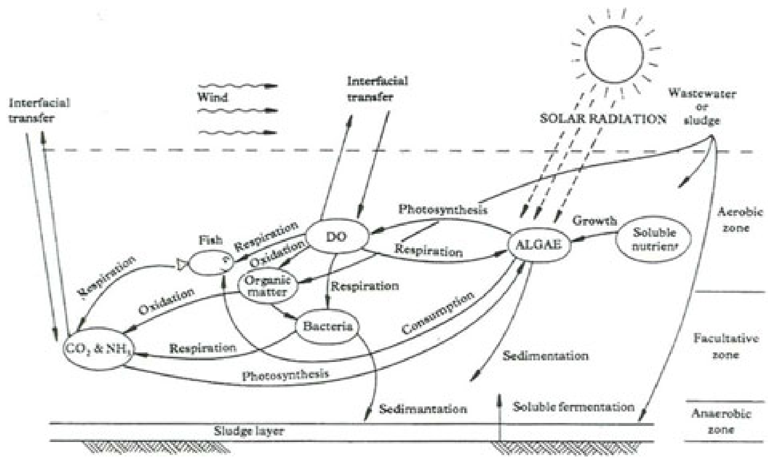


Figure 6.5 A simplified view of septage-fed fish pond dynamics (adapted from Bhattrai 1985)

The above biochemical reactions normally result in diurnal changes in pH and DO in the pond water as shown in Figure 6.6. The basic phenomena involved are that during the dark periods, photosynthetic activity ceases to function and the algal cells do not utilize the CO_2 released by bacterial decomposition of organic matter, resulting in the formation of carbonic acid and, consequently, a decrease in pH. Biomass respiration and the absence of photosynthesis during night time contribute to a drop in DO. With the onset of the light period, the algae consume CO_2 for photosynthesis with the production of oxygen and more algal cells, this results in a gradual increase in pH and DO (upto supersaturation level) in the pond water. In Figure 6.6, the DO at dawn did not reach zero because the applied organic loading was not excessive. Since fish are generally sensitive to low DO, organic loadings to be applied to fish ponds should be properly controlled so that the DO level at dawn, the critical period, does not become zero. Otherwise, some kinds of mechanical aeration need to be provided to the fish ponds to avoid fish suffocation.

6.5 ENVIRONMENTAL REQUIREMENTS AND DESIGN CRITERIA

6.5.1 Environmental requirements

To enhance the fish growth in waste-fed ponds, various environmental parameters should be properly maintained or acquired, as follows:

Light

Light should be in sufficient intensity and with suitable duration during the daytime. It is the main factor in algal photosynthesis, which results in the production of fish feed (algal cells) and oxygen for fish respiration. Generally this requirement is always met in tropical area where depth of fish ponds is maintained at about 1 m to allow for light penetration to the whole pond depth.

Temperature

Fish metabolic rate is directly correlated with water temperature. Heut and Timmermans (1971) reported that temperature has a considerable influence on the principal and vital activities of fish, notably their breathing, growth and reproduction. Increased temperature will lower the DO in the water (according to Table 6.3) and also increase the metabolism of fish, which require more oxygen. The temperature tolerance limit within each species with individuals of different ages is the same, but the limit is different if they are acclimatized at different temperatures. Unfavourable temperatures at either end of the tolerance range produce a stress in which a prolonged exposure could result in lowered resistance and greater susceptibility to disease. Temperature does affect metabolism as well as food intake. Hickling (1971) reported that carp stop feeding at about 10°C, and become torpid at about 5°C; trout cease to feed at about 8°C.

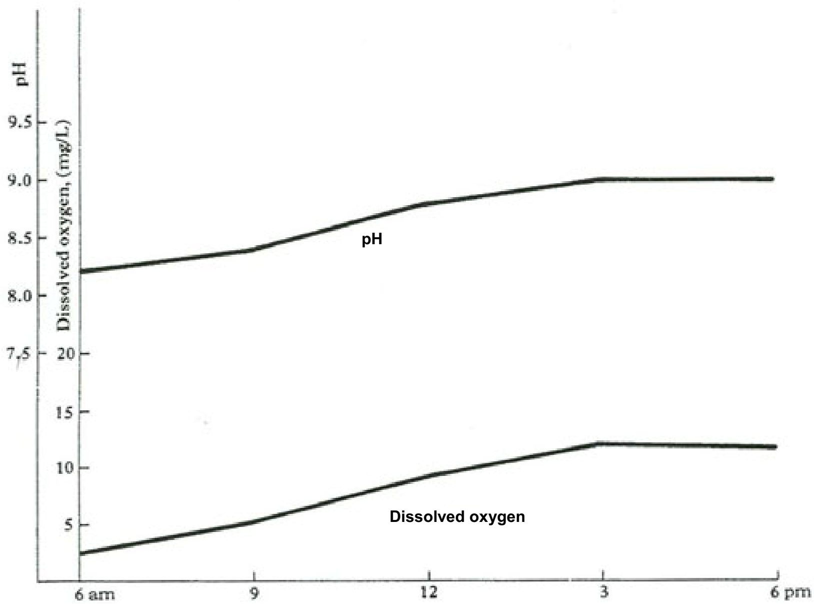


Figure 6.6 Semi-diurnal studies of the septage-fed pond system. Dissolved oxygen and pH were measured at 3 hr interval from 6 a.m. to 6 p.m. on four occasions. Mean of 15 septage fed ponds with fish stocking densities of 3, 6, 9, 12, and 15 /m^2 in triplicate (Polprasert *et al.* 1985)

Dissolved oxygen (DO)

DO is an important factor in the growth of fish because all metabolic activities of fish are dependent on the oxygen consumed during respiration. As shown in Figure 6.6, DO in a waste-fed pond have diurnal variation. Factors affecting the variation of DO include organic loading, algal concentration, type of fish, fish stocking density, sludge accumulation, temperature and chloride concentration (Table 6.3). Organic loading to a pond has influence on the bacterial activity in waste stabilization and, consequently, the oxygen utilization (Equation 2.1). Therefore, to design a waste-fed fish pond, organic loading and fish stocking density have to be properly selected so that the lowest DO to occur in the pond at dawn is within the tolerable range for fish.

Table 6.3 Solubility of dissolved oxygen in water in equilibrium with dry air at 760 mm Hg and containing 20.9 percent oxygen (after Whipple and Whipple 1911)

Temperature ^0C	Chloride concentration (mg/L)				
	0	5000	10,000	15,000	20,000
0	14.6	13.8	13.0	12.1	11.3
1	14.2	13.4	12.6	11.8	11.0
2	13.8	13.1	12.3	11.5	10.8
3	13.5	12.7	12.0	11.2	10.5
4	13.1	12.4	11.7	11.0	10.3
5	12.8	12.1	11.4	10.7	10.0
6	12.5	11.8	11.1	10.5	9.8
7	12.2	11.5	10.9	10.2	9.6
8	11.9	11.2	10.6	10.0	9.4
9	11.6	11.0	10.4	9.8	9.2
10	11.3	10.7	10.1	9.6	9.0
11	11.1	10.5	9.9	9.4	8.8
12	10.8	10.3	9.7	9.2	8.6
13	10.6	10.1	9.5	9.0	8.6
14	10.4	9.9	9.3	8.8	8.3
15	10.2	9.7	9.1	8.6	8.1
16	10.0	9.5	9.0	8.5	8.0
17	9.7	9.3	8.8	8.3	7.8
18	9.5	9.1	8.6	8.2	7.7
19	9.4	8.9	8.5	8.0	7.6
20	9.2	8.7	8.3	7.9	7.4
21	9.0	8.6	8.1	7.7	7.3
22	8.8	8.4	8.0	7.6	7.1
23	8.7	8.3	7.9	7.4	7.0
24	8.5	8.1	7.7	7.3	6.9
25	8.4	8.0	7.6	7.2	6.7
26	8.2	7.8	7.4	7.0	6.6
27	8.1	7.7	7.3	6.9	6.5
28	7.9	7.5	7.1	6.8	6.4
29	7.8	7.4	7.0	6.6	6.3
30	7.6	7.3	6.9	6.5	6.1

Fish species have different rates of oxygen consumption, which vary with the different stages of life. Young fish need more DO than adult fish. Among the various species, Tilapias are the most resistant to low DO. Among carps, common carp is more resistant than silver carp. Most of the data concerning the tolerance to low DO were mainly derived from experiments conducted at constant DO, thus have little relevance to waste-fed ponds where DO fluctuate to a wide extent. Fish may be much more resistant to low DO for a short period of time. Waste-fed fish ponds should be designed to have lowest DO levels of 1-

2 mg/L at dawn, otherwise some kinds of mechanical aeration (e.g. surface aerator) has to be provided during this critical period.

Experiments were conducted at the Asian Institute of Technology (AIT), Bangkok, to observe the effects of adding septage at the loadings of 50, 150, 250 and 350 kg COD/(ha-day) to concrete ponds (the working dimensions of each pond were 2x2x0.9 m^3: length x width x depth). Septage loading to these ponds was conducted once daily, and the data reported in Figure 6.7 are the mean values obtained during steady-state conditions (based on relatively constant COD concentrations in the pond water). The concentrations of algae and NH_3-N were found to increase with increasing septage loadings, while the levels of DO at dawn decreased at high septage loadings, according to the phenomena described in section 6.4. It appears from Figure 6.7 that, under this ambient condition, septage loadings in the range of 50-150 kg COD/(ha-day) should result in suitable DO levels at dawn for Tilapia growth.

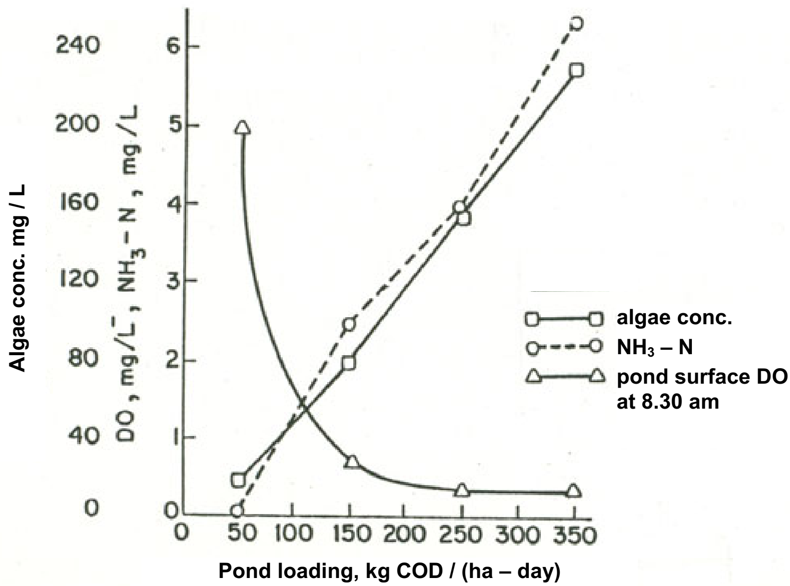
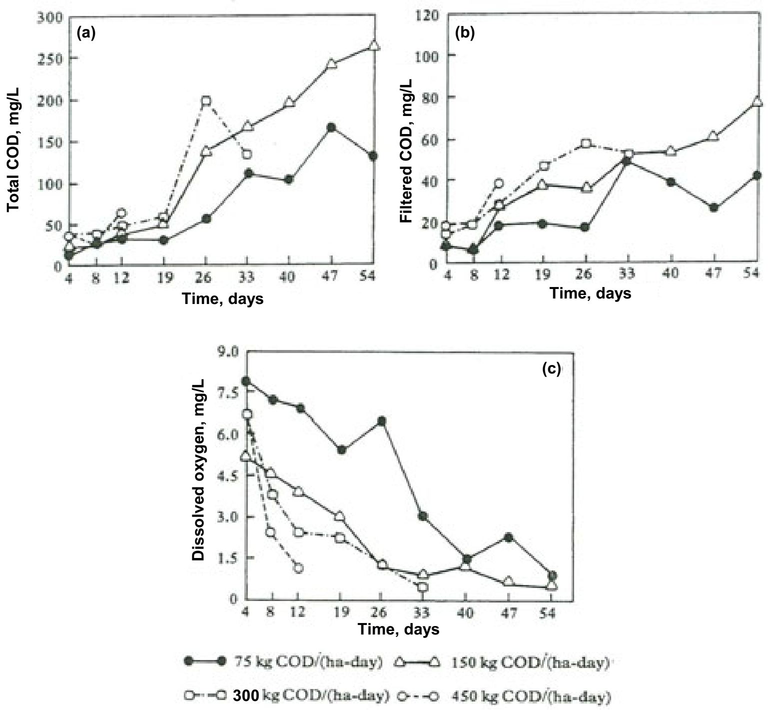


Figure 6.7 Effects of septage loadings on pond characteristics (no fish culture) from Polprasert *et al.* (1984); reproduced with permission of Pergamon Books Ltd

Sharma *et al.* (1987) investigated the variation with time of DO levels at dawn and COD concentrations in the pond water fed with septage at various organic loadings. Their experiments were conducted at AIT campus, Bangkok, under ambient, tropical conditions. Because the pond system used was static and non-flow-through, and septage loading was undertaken once a day, the total and filtered COD concentrations of the pond water increased gradually with respect to time (Figure 6.8 a and b). The increase in COD consequently resulted in a decrease of DO at dawn as observed in Figure 6.8 c.



(a) Variation of total COD
(b) Variation of filtered COD
(c) Fluctuation of dissolved oxygen (DO) at dawn

Figure 6.8 Variations of COD and DO in septage-fed ponds at various COD loadings (Sharma *et al.* 1987; reproduced by permission of Elsevier Science Publishers, B.V)

A portion of the COD increase could be due to the anaerobic decomposition of the settled septage (or sludge) occurring in the sludge layer, which released or resulted in the solubility of some organic compounds to the pond water. These organic compounds were further decomposed by the facultative bacteria and the algal-bacterial symbiotic reactions taking place in the aerobic zone, hence a decrease in the DO level. The filtered COD concentrations of the pond loaded at 75 kg COD/(ha-day) became relatively stable (or attaining steady-state conditions) after about 40 days of operation (Figure 6.8 b), similar to that of the DO level (Figure 6.8 c).

Ponds fed with wastewater or algal-laden water will have diurnal variation of DO similar to the septage-fed ponds. However, there will be less sludge accumulation at the bottom layer, and COD concentrations in the pond water should fluctuate less than those in the ponds fed with sludge.

Ammonia concentration

Un-ionized ammonia (NH_3) is toxic to fish, but the ammonium ion (NH_4^+) is not. Many laboratory experiments of relatively short duration have demonstrated that the acute lethal concentrations of NH_3 for a variety of fish species lie in the range 0.2-2.0 mg/L (Alabaster and Lloyd 1980). Un-ionized ammonia is more toxic when DO concentration is low. However, this effect is probably nullified in fish ponds since CO_2 concentrations are usually high when DO levels are low and the toxicity of NH_3 decreases with increasing CO_2 (Boyd 1979).

The relationship between NH_3 and NH_4^+ is pH-dependent, as follows:

$$NH_3 + H^+ \leftrightarrow NH_4^+ \tag{6.1}$$

Equation 6.1 indicates that NH_3 formation is favored under high pH or alkaline conditions as shown in Figure 6.8.

High concentrations of total ammonia ($NH_3 + NH_4^+$ or NH_3 -N) can occur following phytoplankton die-offs, but abundant CO_2 production associated with such events depresses pH and the proportion of the total ammonia present as NH_3 (Equation 6.1). NH_3 also increases the incidence of blue-sac disease in the fry of freshwater fish when the eggs were cultured in water with high NH_3 content (Wolf 1957). Considering some safety factor, the U.S. Committee on Water Quality Criteria (1972) has recommended that no more than 0.02 mg/L NH_3 be permitted in receiving waters. Sawyer *et al.* (2003) concluded that ammonia toxicity would not be a problem in receiving waters with pH below 8 and NH_3-N concentrations less than 1 mg/L.

pH

Huet and Timmermans (1971) stated that the best water for fish cultivation is that which is neutral or slightly alkaline, with a pH between 7.0 and 8.0. Reproduction diminishes at pH value below 6.5 and growth rate becomes lower at pH range of 4 to 6.5.

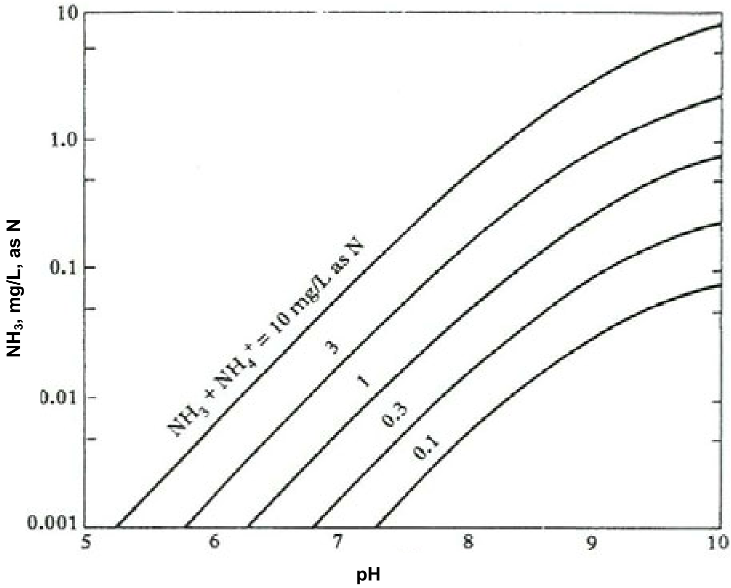


Figure 6.9 Effects of pH and ammonia nitrogen concentration (NH_3+ NH_4^{+}) on the concentration of free ammonia in water (Sawyer *et al.* 2003: reproduced by permission of McGraw-Hill Book Company)

Carbon dioxide

The presence of free CO_2 may depress the affinity of fish blood for oxygen. Fish can sense small differences in free CO_2 concentration and apparently attempt to avoid area with high CO_2 levels. Nevertheless, 10 mg/L or more of CO_2 may be tolerable provided DO concentration is high. Water with less than 5 mg/L of CO_2 is preferable. The most detrimental effect of free CO_2 results during the period of critically low DO (Boyd 1979).

Stocking density

In addition to the limitations imposed by the available oxygen, the density of fish population can increase to the point of growth inhibition. Overcrowding can result in a reduction in growth rate due to stress and competition for food, oxygen and space, and in poor food utilization caused by wastage. It is generally known that there is a limit to the density at which fish can be stocked in ponds, for beyond a certain point, the advantage of growing a larger population of fish is cancelled by the slower growth of the fish, in spite of an excess of food.

Figure 6.10 shows some experimental results of mean weight of fish being cultured at different stocking densities (SD) in earthen ponds, but at a constant organic loading of 150 kg COD/(ha-day). Each pond had a dimension of $20 \times 10 \times 1$ m^3 (length × width × depth). These data clearly show the effects of SD on the mean fish weight. After 6 months of operation, the highest mean fish weight of 118 g was observed in the pond having a SD of 1 fish/m^2, while the lowest mean fish weight of 27 g occurred in the pond with a SD of 20 fish/m^2.

The data from Figure 6.10 were used in plotting Figure 6.11 to show the effects of SD on the mean fish weight and total fish yield. It can be seen that although a lower SD could give a higher individual fish weight, it resulted in a lower total fish yield; the opposite took place in case of a high SD. This information implies that fish to be used as human food should be reared at a low SD to obtain table-size fish. Fish to be used as animal feed can be reared at a high SD to maximize the total fish yield; these fish, small in size, may be used directly or processed further prior to being used as animal feed.

Hydrogen sulfide (H_2S)

Un-ionized H_2S, mainly from anaerobic decomposition of bottom sludge, is extremely toxic to fish at concentrations that may occur in natural waters. Results from various bioassay studies suggest that any detectable concentration of H_2S should be considered detrimental to fish production (Boyd 1979).

Sulfide formation often occurs in anaerobic and facultative waste stabilization ponds due to the reduction of sulfate (SO_4^{2-}) under anaerobic conditions:

$$SO_4^{2-} + \text{organic matter} \xrightarrow[\text{bacteria}]{\text{Anaerobic}} S^{2-} + H_2O + CO_2 \tag{6.2}$$

$$S^{2-} + 2H^+ \longrightarrow H_2S \tag{6.3}$$

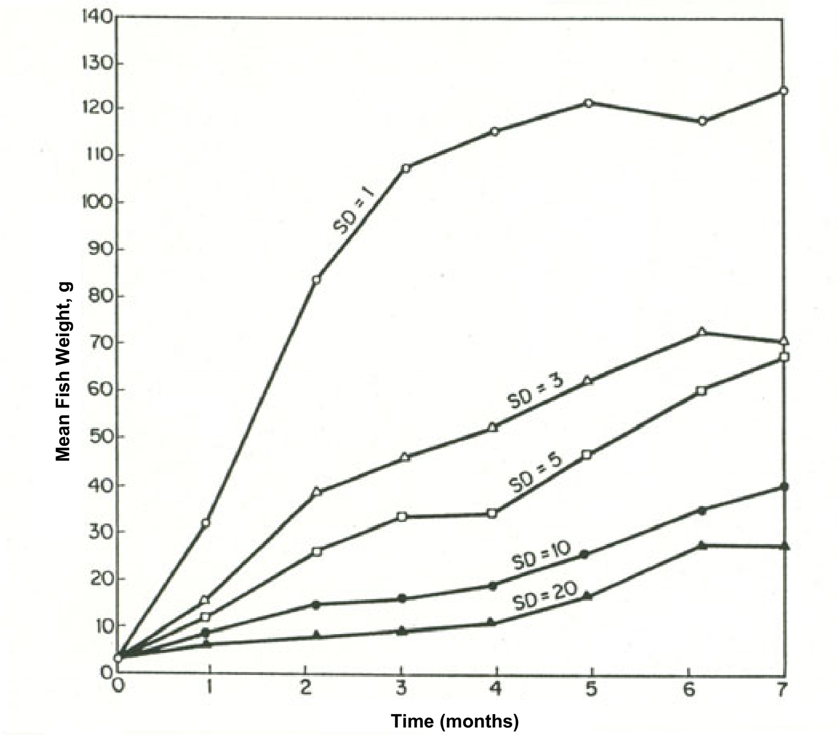


Figure 6.10 Mean individual fish weight (g) at monthly intervals in the septage-fed fish pond system. Each point is a mean of three ponds. Organic loading = 150 kg COD/ (ha-day). Stocking densities (SD) in number of fish/m^2 (Edwards *et al.* 1984)

The relationships between H_2S, HS^- and S^{2-} at various pH levels are shown in Figure 6.12. At pH values of 8 and above, most of the reduced sulfur exists in solution as HS^- and S^{2-} ions, and little amount of un-ionized H_2S, the malodorous gas, is present. However, the formation of un-ionized H_2S is significant at pH levels below 8, which can cause detrimental effects to fish production and producing the malodorous problems.

It is interesting to note that, although an increase in water pH to above 8 can avoid H_2S formation, this pH condition would enhance the formation of the un-ionized NH_3 compounds (see Figure 6.9), which is toxic to fish. Therefore organic loadings to fish ponds have to be properly controlled to avoid the occurrence of anaerobic conditions and DO depletion. Sludge deposits should be periodically removed from the ponds so that anaerobic reactions at the bottom layers are kept to a minimum.

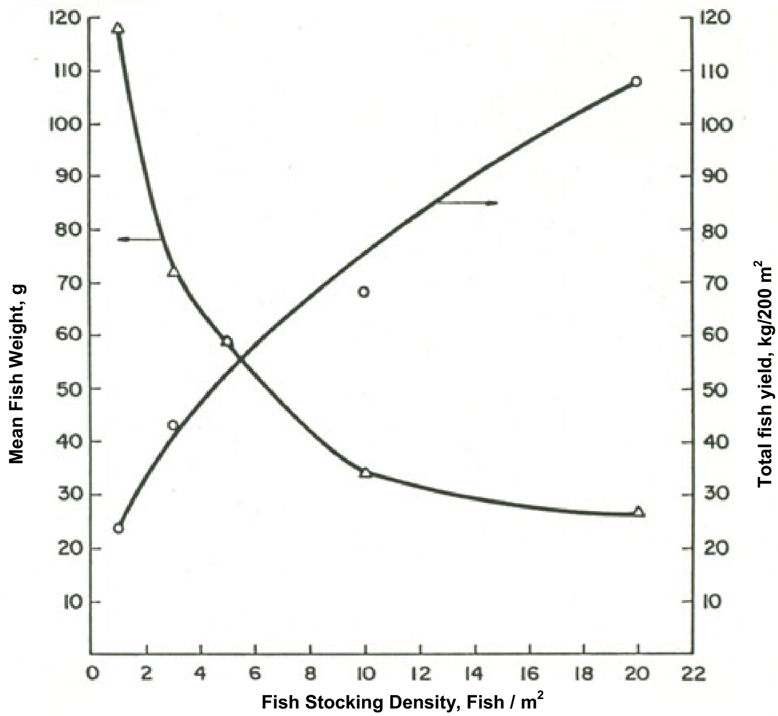


Figure 6.11 Effects of fish stocking density on mean fish weight and total fish yield after 6 months of pond operation. Data obtained from Figure 6.10 and assuming no fish mortality and no spawning

Heavy metals and pesticides

These compounds, either individually or in combination, can produce acute toxicity to fish at concentrations as low as a few μg/L, and the extent of toxic effects depends on several factors such as water quality; species, age and size of fishes; and antagonistic and synergistic reactions occurring in the pond water. Long-term effects of these compounds may include decline in growth rate and reproduction, and the enhancement of bioaccumulation and biomagnification in the food chains as described in section 6.3.

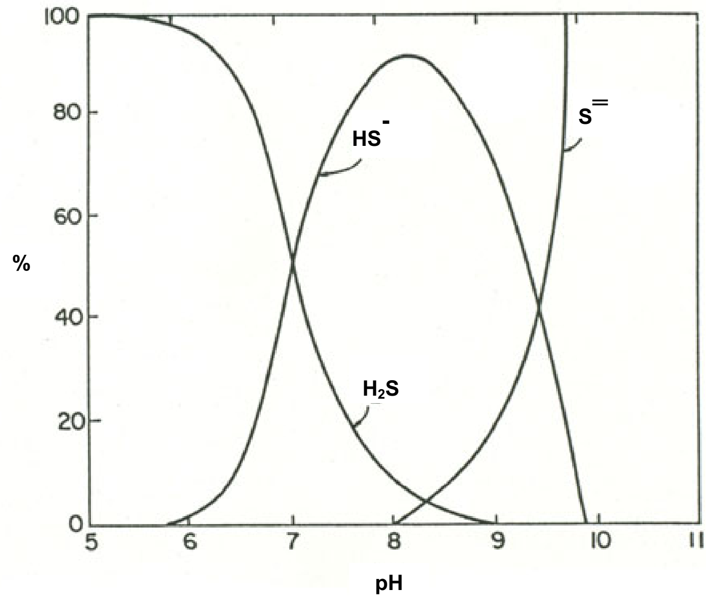


Figure 6.12 Effect of pH on hydrogen sulfide-sulfide equilibrium (after Sawyer *et al.* 2003; reproduced by permission of McGraw- Hill Book Company)

6.5.2 Design criteria

Organic loading, DO and fish yield models

Almost all kinds of organic wastes can be fed to fish ponds. These wastes can be in any of the following forms: raw sewage, effluents from wastewater treatment plants or high-rate algal ponds, nightsoil and septage, biogas slurry, composted products, animal manures, and agro-industrial wastewaters. Fish may be reared directly in waste stabilization ponds. In any case, organic loadings to be applied to waste-fed fish ponds should be in the range that anaerobic conditions do not prevail in the ponds.

Data in Table 6.1 show that well-operated fish ponds fed with wastewater had organic loadings in the range of 25-75 kg BOD_5 /(ha-day), while those fed with organic solids e.g. septage or biogas slurry had organic loadings from 50 to 150 kg COD/(ha-day). Data of fish yields vary widely depending on the modes of pond operation, climates, fish species and stocking densities employed.

However, these fish yield data were reported to be at least comparable to or better than those ponds fed with conventional fish feed.

DO-at-dawn (DO_d) model

Since the critical period of DO depletion in fish ponds occurs during night time or the early morning period, a model to predict this critical DO (or DO_d) would be useful for fish pond operators. Boyd (1979) proposed a mass-balance equation to estimate the amount of DO remaining at dawn.

$$DO_d = DO_{dusk} \pm DO_{df} - DO_f - DO_{in} - DO_p \tag{6.4}$$

Where,
DO_d = DO concentration at dawn, mg/L
DO_{dusk} = DO concentration at dusk, mg/L
DO_{df} = gain or loss of oxygen due to diffusion, mg/L
DO_f = DO used by fish, mg/L
DO_m = DO consumed by sediment, mg/L
DO_p = DO used by planktonic community, mg/L

To determine DO_d from Equation 6.4, values of the parameters on the right hand side have to be determined, either experimentally or obtained from literature. Computer simulations programs have been developed by Boyd (1979), which could model the dynamics or fluctuation of DO_d in channel catfish ponds satisfactorily.

From a practical point of view, DO_d model should be a simple one to enable fish pond operators to easily determine the occurrence of critical DO, so that appropriate measures (such as mechanical aeration or temporary discontinuation of organic waste feeding) can be undertaken. Bhattarai (1985) proposed an empirical DO_d model for waste-fed fish ponds as follows:

$$DO_d = 10.745 \exp \{-(0.017\, t + 0.002\, L_c)\} \tag{6.5}$$

Where,
exp = exponential
t = time of septage loading, days
L_c = cumulative organic loading to fish ponds up to time t, kg COD (per 200 m^3 pond volume).

Equation 6.5 was developed and validated with experimental data of Edwards *et al.* (1984), as shown in Figure 6.13 for the experiments with a septage loading of 100 kg COD/(ha-day). These experiments were conducted in Thailand with earthern ponds, each with working dimensions of 20x10x1 $m^{3:}$ length x width x depth. These ponds were daily fed with septage at organic loadings of 50, 100, 150, 200, 250 and 300 kg COD/(ha-day), and Tilapia stocking densities were varied at 1, 3, 5, 10 and 20 fish/m^2. The ponds were operated as "non-flow-through" in which there was no effluent overflow, but canal water was periodically added to make up for water losses due to evaporation and seepage. It is apparent that Equation 6.5 is applicable to only the above experimental conditions. Other types of fish pond conditions and operation will have different coefficient values for Equation 6.5, but the effects of t and L_c on DO_d might be similar.

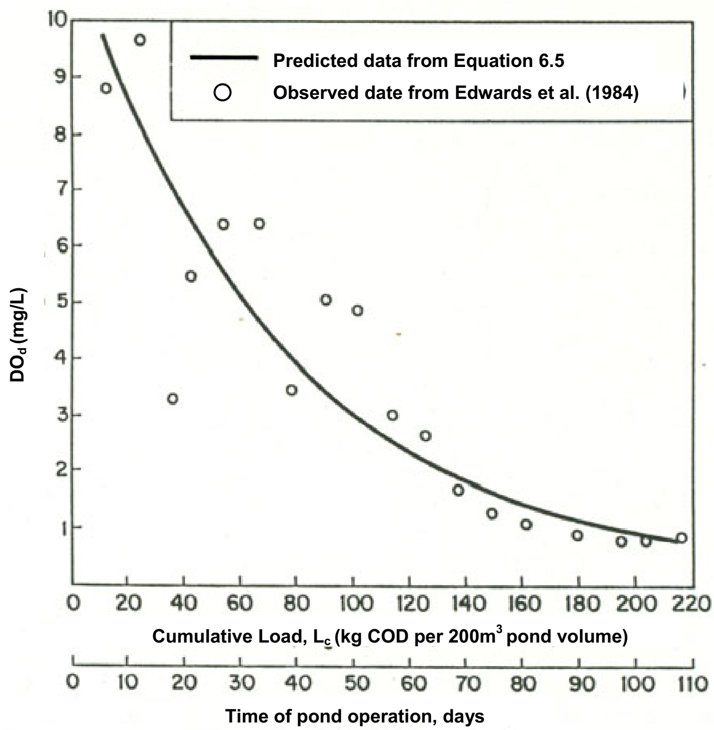


Figure 6.13 Cumulative load versus DO_d for 100 kg COD/(ha-day) loaded septage ponds

The trend of DO_d decline with time as shown in Figures 6.8 and 6.13 is usually expected in fish ponds fed with organic wastes such as septage, sludge or manure. This phenomenon is due to the pond hydraulics that are static and without effluent overflow. All the loaded organic wastes stay in the ponds and exert an oxygen demand which keeps on increasing due to the accumulation of the residual organic compounds and solubilization of some organics from the sediment layer (see Figures 6.8 a and b). After some period of pond operation, the DO_d level seemed to reach a plateau in which a further decline of DO_d was not observed much, an indication of a somewhat steady-steady condition with respect to DO_d dynamics in the waste-fed ponds.

For the flow-through ponds fed with wastewater, there is effluent flow that is more or less equal to that of the influent flow. In this case there is less sediment accumulation at the pond bottom and consequently less variation of the DO_d concentration with time of pond operation.

Tilapia growth model

An empirical model of Tilapia growth in septage-fed fish ponds was developed by Bhattarai (1985) using the data of Edwards *et al.* (1984). The model considered the effects of: a) fish stocking density (SD), as evidenced from Figure 6.11; b) nitrogen loading, as nutrient source for algal growth (or Tilapia food); and c) time of fish culture. The effect of initial fish weight was not included because all the fish stocked had approximately the same initial weight of about 2.7 g. The developed model, assuming a constant temperature of 30 °C and neglecting spawning, is

$$W_t = 12.032\ (t.N/SD)^{0.707} \qquad (6.6)$$

Where:

W_t = mean fish weight at time t, g

t = time of fish rearing, months

N = total Kjeldahl nitrogen (organic N + NH_3-N + NH_4-N) loading, kg/(ha-day)

SD = fish stocking density, no./m^2

Equation 6.6 is valid when N, t and SD are greater than zero, and the term (t.N/SD) can be interpreted as the applied weight of nitrogen per fish. Figure 6.14 shows a typical relationship between the observed and predicted fish weight (using Equation 6.6) in which a good correlation is observed.

It should be pointed out that the development of Equations 6.5 and 6.6 and their validations were undertaken by using different sets of experimental data. However, it is apparent that, to ensure their applicability, these two equations should be validated further with other field-scale data and with data of fish ponds having different modes of operation, fish species and types of organic waste input.

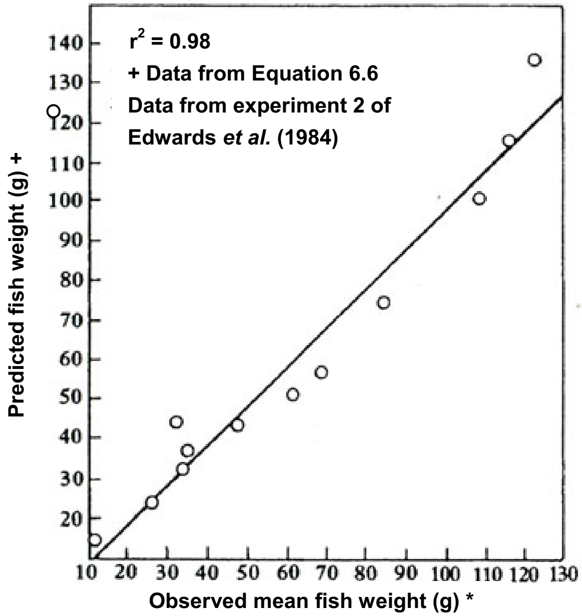


Figure 6.14 Observed versus predicted fish weight for septage-fed pond; SD = 1, 5; COD loadings = 150 kg/(ha-day)

Fish culture and stocking density

Polyculture of fish (such as herbivores and carnivores) is not advisable in waste-fed ponds because of public health considerations due to direct contact of all these fish to the wastewater, even though it utilizes all part of the aquatic environment. It is not practical to design a waste-fed pond to rear different species of fish because their tolerance levels to low DO are different. Also the carnivores might predate the herbivores, thus hampering the potential growth of the herbivores.

Fish sex is an important factor when yield needs to be increased. Due to genetic reasons, male tilapia generally grows faster than their female counterparts (Guerrero, 1982). Monosex male culture of tilapias gives faster growth and eliminated unnecessary reproduction, which can take place during the culture period. Besides the increased yields, the produced male tilapias would be of the same size, easier to be harvested and marketed. Monosex tilapias can be obtained by:

- manual separation of the sexes, which can be difficult when small fish fry is used;
- production of monosex broods through hybridization;
- sex reversal with the use of sex steroids (such as androgen, methyltestosterone and ethynyltestosterone) in the diet of fish fry during the period of gonadal differentiation (or the production of male or female organs). The effectiveness of these steroids was reported to be 93 – 100% (Nacario 1987).

Tilapia species is most suitable for waste-fed ponds due to its hardy characteristics. Other herbivorous fish such as silver carp and bighead carp are also promising species. Polyculture is recommended where benthic feeding fish such as mud carp are stocked together with omnivorous fish like common carp.

Stocking density should be of primary concern in fish culture. As shown in Figure 6.11 and Equation 6.6, high stocking density gives high yield per pond volume, but with the smaller mean size of fish. To produce trash fish for animal feed, stocking density of 10 or more fish/m^2 is recommended and the period of fish culture may be as short as 3 months. Ponds producing marketable-size fish, for possible use as human food, should be stocked at a lower density such as 1-2 fish/m^2 or even less, but the rearing period may be up to 1 year or longer. However, several commercial fish farms are reportedly able to stock fish at densities greater than 50 fish/m^2 provided that pond water quality (listed in section 6.5.1) and fish food are maintained at the levels favourable for fish growth.

Water supply

Water supply should be sufficient in quantity and of good quality since ponds fed with solid or semi-solid organic wastes e.g. animal manures or nightsoil, need a certain amount of water to compensate for losses through evaporation and seepage. Ponds fed with sewage or effluent of wastewater treatment plant sometimes needs dilution water. The quality of water should be in the permissible range for fish growth.

Pond size

Generally pond depth of 1-1.5 m is suitable for fish with the provision of free board of 0.3 to 0.6 m. In rain-fed pond, if the organic input is in solid form, deeper water level should be provided to compensate the water loss during dry season. A polyculture fish pond is recommended to have 2-3 m depth with an area of manageable size; normally the 1,000-4,000 m^2 pond area is suitable in the tropics. The width of ponds should not exceed 30 m to facilitate seining operation. Separate water supply and drainage system should be provided in each pond.

Pond arrangement

Various pond arrangements can be made to suit the local condition as well as type of organic wastes available. Figure 6.15 shows some possible arrangements of the ponds with appropriate measures such as depuration to safeguard the public health (see sections 6.6 and 6.7). In some cases, it might be necessary to drain the fish ponds during or after harvesting. Therefore additional pond area or water storage space should be provided for the drained water to prevent contamination of the fish pond water to the nearby water courses. Depending on the water quality and local conditions, the fish pond water can be used for irrigation. Fish ponds that have been drained should be sun-dried for 1-2 weeks to inactivate any pathogens inhabiting at the pond bottom and side walls. The bottom mud should be removed to maintain the working pond volume and avoiding excessive accumulation of sludge at the pond bottom.

Based on the above information and the data from Edwards (1992), design guidelines and performance data of waste-fed fish ponds are given in Table 6.4.

Table 6.4 Design guidelines and performance data of waste-fed fish ponds

Pond depth (m)	1-1.5
Pond width (m)	< 30
Pond area (m^2)	400-4000
Minimum DO at dawn (mg/L)	1-2
NH_3 concentration of pond water (mg/L)	< 0.02
pH of pond water	6.5-9 (optimum 7.0-8.0)
Organic loading rate	
(kg BOD_5/ha-day)	25-75
(kg COD/ha-day)	50-150
Fish stocking density (fish/m^2)	0.5-50
Recommended fish species	Tilapia and carps
Culture period (months)	3-12
Fish yield (kg/(ha-yr))	1000-10000
Removal efficiencies	
Suspended solids (%)	70-85
BOD_5 (%)	75-90
Total nitrogen (%)	70-80
Phosphorus (%)	80-90

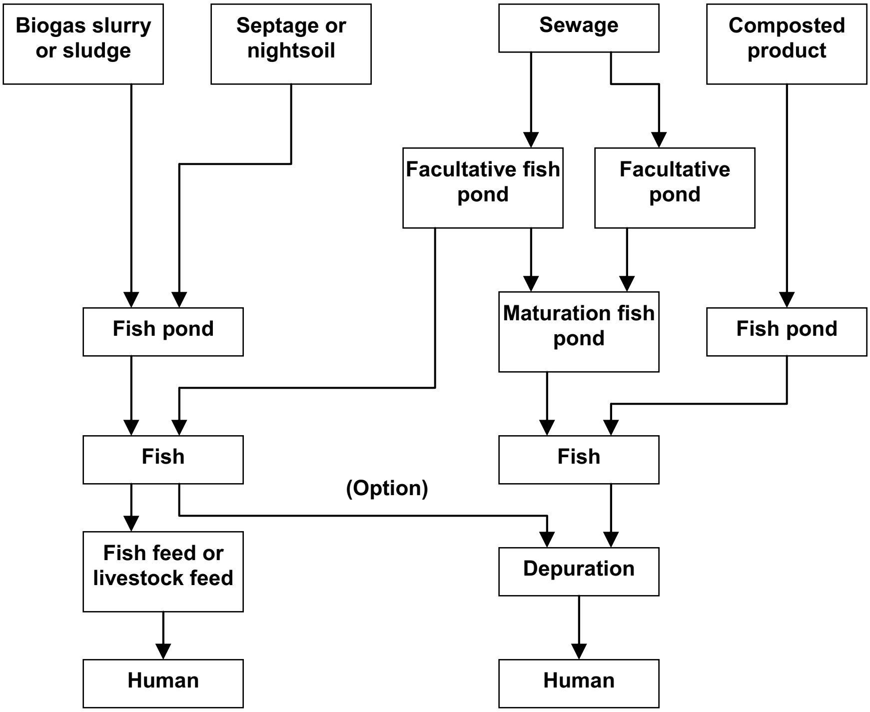


Figure 6.15 Some arrangements of waste-fed ponds

Example 6.1

Design a septage-fed fish pond from the given septage characteristics.

Quantity	10 m^3/day
BOD_5	5,000 mg/L
COD	25,000 mg/L
Org-N	1,500 mg/L
NH_3-N	500 mg/L
Total-P	300 mg/L
Total solids	4.5%
Volatile solids	70% of total solids

Solution

From data presented in Table 6.4 and Figure 6.7,

Use organic loading rate = 50 kg COD/ (ha-day)

$$\text{Area requirement} = \frac{10 \text{ x } 25{,}000}{50 \text{ x } 1{,}000} = 50{,}000 \text{ m}^2 = 5 \text{ ha}$$

Select a fish pond size of 25.0 m (width) x 50.0 m (length) x 1.5 m (depth); water depth = 1.0 m

$$\text{Number of ponds} = \frac{50{,}000}{25 \text{ x } 50} = 40 \text{ ponds}$$

Each pond is separated from each other to facilitate harvesting and drying operation.

Select Tilapia (*Oreochromis niloticus*) with a stocking density of 5 fish/m^2. The products will be sold as trash fish to produce animal feed. This will reduce possible health hazard from direct consumption of these fish.

Number of fingerling (about 0.5-5 g) used = 1,250 x 5 = 6,250 fish/pond.

Select harvesting period of 3 months and 10 days of pond drying or 100 days in total before subsequent operation.

Calculate fish yield from Equation 6.6:

$W_t = 12.032\ (t.N/SD)^{0.707}$

$$N = \frac{(500 + 1{,}500)}{1{,}000} \quad \frac{10}{5} \quad \text{x} = 4 \text{ kg/(ha-day)} \qquad (6.6)$$

t = 3 months

SD = 5 fish/m^2

$W_t = 12.032(3\text{x}4/5)^{0.707} = 22.3$ g/fish

Assume mortality rate = 20%

$$\text{Estimated fish yield} = 6{,}250 \text{ x } 0.8 \text{ x } \frac{22.3}{1{,}000}$$

= 112 kg/pond per 100 days

$$\text{Extrapolated fish yield} = 112 \text{ x} \frac{365}{100} = 408.8 \text{ kg/(pond-year)}$$

$$= \frac{408.8}{0.125} = 3{,}270 \text{ kg/(ha-year)}$$

Estimated total fish yield = 5 ha x 3,270 kg/(ha-year) = 16,350 kg/year
Calculate DO at dawn (DO_d) from Equation 6.5:

DO_d = 10.745 exp [-(0.017t + 0.002 L_c)] (6.5)
t = 90 days
L_c = Cumulative COD loading in pond = 50 x 0.125 x 90 = 562.5 kg/(1250 m^3 pond volume)
= 90 kg/(200 m^3 pond volume)
DO_d = 10.745 exp [-(0.017x90 + 0.002x90)] = 1.94 mg/L

Tilapia should be able to survive at this DO_d level of about 2 mg/L. Or organic loading to this fish pond can be a little more than 50 kg COD/(ha-day) because Tilapia can tolerate DO level of about 1 mg/L.

6.6 UTILIZATION OF WASTE-GROWN FISH

Waste-grown fish may be used as:

- A source of animal protein in human diet
- Fish meal or feed for other animals

6.6.1 Human consumption

The fish to be used for human consumption should be bigger in size, safe from pathogens and helminths, and have nutrition equal to or higher that obtained from other sources of fish. Size can be obtained by increasing the nitrogen loading, lengthening the rearing period, and using a lower stocking density or stocking with monosex male fish.

The following measures are believed to reduce the transfer of pathogens such as: raising carnivorous fish for human consumption using the herbivorous fish from waste-fed ponds as feed; pretreatment of waste input so that its microbiological quality meets the standards for aquacultural reuse stated in Table 2.28; depuration which is a natural process to remove some microorganisms or toxic and malodorous compounds from the fish body by putting contaminated fish in clean water for 1-2 weeks; and finally public education to wash, to remove intestines and to cook the fish well before consumption. Nutritional value of waste-grown fish has shown to be better than those grown using other sources of feed. Most of the nutrition applied in the form of waste is converted to protein rather than fat as reported by Moav *et al.* (1977) and Wohlfarth and Schroeder (1979).

6.6.2 Fish meal or feed for other animals

This method of utilization is suitable for the fish grown directly on waste, in order to lengthen the food chain and to reduce the possibility of transference of pathogens. The waste-grown fish can be used as feed for carnivorous fish or shrimps, which have high market value when sold for human consumption. Biological value of protein in fish meal is 74-89% which is quite high (Williamson and Payne 1978) suitable for feeding to pigs and chicken. For this purpose, fish in waste-fed ponds can be reared at a higher stocking density and shorter growing period to obtain high fish yield. Fish can be sun-dried, grounded, and mixed with other food stuffs to increase the value of fish meal.

Experiments were conducted at AIT to investigate the feasibility of using Tilapia grown in septage-fed ponds as fish feed ingredients for carnivorous fish of high market value such as snakehead (*Channa striata*) and walking catfish (*Clarias batrachus* and *C. macrocephalus*) (Edwards *et al*. 1987 b). Tilapia harvested from the septage-fed ponds was used either fresh, or processed, as silage and mixed with other feed ingredients prior to feeding to the carnivores. A silage was produced by adding 20% carbohydrate (cassava) to minced Tilapia (weight/weight) in the presence of *Lactobacillus casei*. It was found that growth of these carnivorous fish in ponds fed with Tilapia fish meal, fresh Tilapia or silaged Tilapia were comparable with that fed with marine trash fish (conventional fish feed), but poor food conversion efficiencies were obtained because of excessive rate of feeding (Table 6.5).

Table 6.5 Comparison of growth and food conversion ratios of carnivorous fish fed with different feeds (Edwards *et al.* 1987)[a]

	Channa striata			*Clarias macrocephalus*		
	MWG (g)	DWG (g/d)	FCR	MWG (g)	DWG (g/d)	FCR
Marine trash fish feed	26.03	0.30	14.15	35.08	0.26	13.88
Tilapia meal feed	45.77	0.59	33.18	43.84	0.33	12.53
Tilapia silage feed	55.37	0.65	6.45	47.67	0.36	10.15
Fresh tilapia	52.81	0.62	10.99	51.43	0.39	12.87

[a] MWG = mean weight gain; DWG = daily weight gain; FCR = food conversion ratio.

Data in Table 6.5 were obtained by using a feeding rate of 20% body weight/day. In studies in which excellent FCRs of 2.5 or less were reported, a feeding rate of less than 10% body weight/day was used (Edwards *et al.* 1987).

6.7 PUBLIC HEALTH ASPECTS AND PUBLIC ACCEPTANCE

Since organic wastes such as sludge and animal manure can contain a large number of pathogens, fish rearing in a waste-fed pond obviously have a risk of becoming contaminated by these pathogens. In this regard, fish are considered to be indicators of the sanitary condition of the fish pond water, in which the microbial flora present in the fish body directly reflects the microbiological condition of the water from which they are taken.

According to Feachem *et al.* (1983), three distinct health problems associated with fish culture in ponds enriched with human and/or animal wastes are:

- The passive transference of pathogens by fish, which become contaminated in polluted water.
- The transmission of certain helminths whose life cycles include fish as an intermediate host, and
- The transmission of other helminths with a life cycle involving other pond fauna such as snail hosts of schistosomes.

The first problem is a cause of concern worldwide, whereas the second and third apply only in areas where the helminths concerned are endemic.

The passive transference of pathogens occurs because fish can carry these pathogens, especially bacteria and viruses on their body surfaces or in their intestines, which can later contaminate people who handle or eat these fish raw or partially cooked. Pilot-scale experiments on waste-fed ponds were conducted at the AIT using septage, composted nightsoil and biogas slurry as organic wastes feeding into Tilapia ponds (Polprasert *et al.* 1982 and Edwards *et al.* 1984). Within the organic loadings upto 150 kg COD/(ha-day), the total coliform and fecal coliform bacteria and the *E.coli* bacteriophages (a viral indicator) were found to be absent in the various fish organ samples such as blood, bile and meat. These microorganisms were found at high densities in the fish intestines (up to 10^9/mL), as normally expected. The levels of total coliforms and fecal coliforms in the fish pond water were 10^3-10^4 no./100 mL, comparable to those in the control ponds without septage feeding.

Fish have been shown not to be susceptible to the same enteric bacterial diseases of humans and animals (Allen and Hepher 1976; and Jansen 1970). Therefore, several human bacterial pathogens, which have been shown to be carried in and on fish (Jansen 1970), may be carried passively, infecting only the gut surface, which can be cleaned by depuration. Studies of human pathogens in salmonides reared in Arcata wastewater fish ponds, in California, showed bacteria causing human infections only in the gut (Allen *et al.* 1976). Results from kidney, liver and spleen samples indicated that none of the potential pathogens were present in these fish organs under the fish culture conditions in Arcata.

Cloete *et al*. (1983) reported that the skin, gills and intestines of the waste-grown fish from a pond system treating cattle feedlot effluents contained large numbers of bacteria, including potential pathogens. However, similar bacterial numbers, including potential pathogens, were also associated with the skins, gills and intestines of naturally grown fish. This suggests that the health risk involved in the consumption of waste-grown fish might not be substantially different to that of natural fish populations. In both cases, the tissues and blood appeared to be sterile, which would contribute to a much reduced health risk.

From the above information, it appears that bacteria are normally present in fish intestines. However, if bacteria are present in very high concentrations in the fish pond water or the fish body, the natural immunological barrier of fish could be overcome and the bacteria could invade the fish meat. Buras *et al.* (1985) defined a "threshold concentration" as the number of bacteria which, when inoculated into the fish, causes their appearance in the fish meat. From their experiments with Tilapia and carp, a list of threshold concentrations is given in Table 6.6. Depuration experiments were found to be effective when the fish did not contain high concentrations of bacteria in their meat. With respect to the microbiological quality of fish pond water, Buras *et al.* (1987) experimentally found the 'critical concentration' of standard plate count bacteria to be $5x10^4$ no./mL, in which bacterial concentrations higher than this critical concentration were found to cause their appearance in the meat of the fish reared in the ponds.

Hejkal *et al.* (1983) investigated the levels of bacteria and viruses in fish reared in experimental wastewater-fish ponds in Arkansas, U.S.A. They found that even when levels of bacteria exceeded 10^5/100g in the fish guts, very little penetrated into the fish muscle tissue; the maximum of 25 fecal streptococci/100 g was found in the fish meat. They finally suggested that while the fish do not accumulate bacteria in the muscle tissue, contamination of the muscle tissue during processing is difficult to avoid. Buras *et al.* (1985) proposed that to prevent serious public health problems, the threshold values in Table 6.6 should be considered satisfactory criteria for the design and management of fish ponds in which wastewater is used. In addition, since the experiments performed with Polio 1 LSc viruses suggested a very low threshold concentration, and since viruses have a low infective dose, their presence in the fish pond water or wastewater to be fed to the fish pond should be of a major concern.

The second public health problem is related to the helminths requiring fish as intermediate hosts. The major and common types of these helminths associated with waste-fed fish ponds include *Clonorchis* and *Opisthorchis* (Feachem *et al.* 1983). The excreted eggs of these helminths, once discharged into a pond, will release miracidium (a larvae), which after ingested by specific species of freshwater snails will develop and multiply into free-swimming cercarial larvae. Within 1-2 days these cercaria have to find a fish as second intermediate host, in which they penetrate under the fish scales and forming cysts in the connective tissues. When the fish are eaten raw or partially cooked, the cysts enter the human body and developing into worms in the digestive tract. Female worms will lay eggs, which will come out with the feces. If this feces is discharged into a pond, this transmission cycle of the helminths could start again.

The third public health problem concerns with schistosomiasis in which specific species of freshwater snails serve as intermediate hosts for certain *Schistosome* helminths. The schistosome eggs that are discharged into a pond will release miracidium. After ingested by the snails, these miracidium will develop and multiply into infective cercarial larvae that can penetrate directly into human skin. Once entered human body, these cercaria will develop into mature worms and the female worms will lay eggs that will come out with the feces again, and the transmission cycle is repeated.

Table 6.6 Threshold concentrations of microorganisms inoculated to fish (adapted from Buras *et al.* 1985)

Micro organisms	Threshold concentration, no/fish	
	Tilapia aurea	*Cyprinus carpio*
Bacteria		
E. coli	$2.5\text{x}10^6$	$1.5\text{x}10^6$
Clostridium freundii	$9.3\text{x}10^3$	-
Streptococcus faecalis	$1.9\text{x}10^4$	$4.0\text{x}10^4$
Streptococcus Montevideo	$1.8\text{x}10^4$	$3.7\text{x}10^4$
Bacteriophages		
T2 Virus	$4.0\text{x}10^3$	$4.6\text{x}10^3$
T4 Virus	$2.0\text{x}10^4$	-

It appears that the cooking and eating habits of the people will have great impact upon the people who handle and eat the waste-grown fish. Fish that are well cooked will have all the pathogens that are on or in the fish body killed. However, disease transmission during fish harvesting, cleansing, and preparation prior to cooking can occur, depending upon the types of the diseases present. In areas where there are endemics or outbreaks of diseases related to fish ponds, organic wastes to be applied to fish ponds have to be properly treated to ensure destruction of these pathogens, or feeding of organic wastes to fish ponds should be discontinued temporarily. Fish to be used as animal feed will normally have to be processed further e.g. through drying, silaging and/or pelletization which will result in die-off of most pathogens.

Another major problem relating to the consumption of fish raised on wastes is the public acceptability of the fish. As far as taste and texture is concerned, personel observations by various workers indicate that fish grown in well-treated domestic wastes are equal to or even superior in taste or odor to non-wastewater cultivated fish (Allen and Hepher 1976). Fish grown in manure-fed ponds have a different taste and texture since they are much leaner, with only 6% fat, which is excellent compared to fish raised on high protein feed pellets with 15% fat, and fish rose on grain with 20% fat (Wohlfarth and Schroeder 1979).

Probably the most critical prerequisite before we can obtain public acceptance of waste-grown fish is the public health concerns. All legitimate public health concerns must be adequately assessed and resolved and adequate public health safeguards provided. Perhaps a way to overcome this public health problem is to treat the waste prior to use in fish culture to meet the WHO standard for aquacultural reuse (Table 2.28). Lime treatment of sludge can inactivate a large number of bacteria and viruses, but not helminthic ova. Waste stabilization ponds in series or sedimentation basins with a detention time of at least ten days can settle out most of the helminthic ova, but care has to be taken with the second and third types of helminthic problems, described earlier. An increased destruction of pathogens would also take place if the waste were treated by a biogas or composting system before adding to the fish pond since both processes, especially the latter, lead to an increased temperature which kills pathogens. An additional step could involve depuration, the maintenance of the fish in clean water for a week or two, which may eliminate any disease organisms that survived the earlier treatments. The final step would be to have good hygiene in all stages of fish handling and processing, and to ensure that the fish intestines are removed and the meat thoroughly washed and cooked before consumption. Another strategy could involve feeding the waste-grown fish to other animals that can be consumed by humans, so that the fish raised on waste are not consumed directly by humans. Both strategies would reduce the possibility of disease transfer.

Public need will probably determine the degree of public acceptance of waste-grown fish in a particular area. Table 6.1 shows that the practice of fish production in waste-fed ponds, although at a small extent, has been undertaken in both developed and developing countries. The social, economic and political considerations that influence human behaviour are very complicated. However, openness, candour, public education and public involvement appear to be the keys to public acceptance. In spite of the many problems, the future for waste-fish recycling systems seems promising This is due to the ever increasing demands for both waste disposal and food production in today's rapidly expanding populations.

6.8 CHITIN AND CHITOSAN PRODUCTION

The conventional process of chitin production from shrimp shells consists of (a) alkaline treatment of deproteination by using 4% NaOH at 30^{o}C for 24 hours and (b) acid treatment or decalcification by using 4% HCl at 30^{o}C for 24 hours. Chitin is polysaccharides polymers made up of a linear chain of N-acethylglucosamine groups as shown in Figure 6.16.

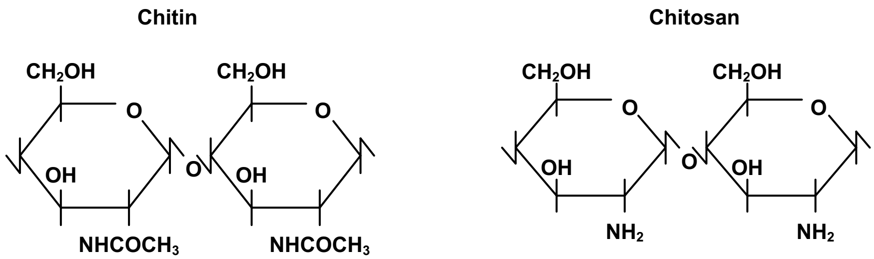


Figure 6.16 Chemical structures of chitin and chitosan

Chitosan is obtained by a process called deacethylation, which treats the chitin compounds in 50% NaOH solution for 24 hours at 30^{o}C or ambient temperatures. The deacethylation reaction remove acethyl groups (CH_3-CO) from the chitin molecules and makes the product, chitosan (see Figure 6.16), cationic in characteristic and soluble in most dilute acids. A schematic diagram of chitin and chitosan production from shrimp shells is shown in Figure 6.17.

To produce chitin from 100 kg of fresh shrimp shells, about 250 L of 4% NaOH and 250 L of 4% HCl would be required for the deproteination and decalcification, respectively; while about 80 L of 50% NaOH is needed for the deacethylation. Chitin content in shrimp shells is in the range of 10-20%.

The application of chitin and chitosan in the various fields is shown in Figure 6.18, while those of chitin in the industrial and medical fields are listed in Table 6.7.

Due to its characteristics chitosan, when dissolved in dilute acids, becomes a cationic polymer that can be effectively used in flocculation, film forming, or immobilization of various biological reagents including enzymes. It can act as a moisturizing agent in cosmetics or used in wound healing and controlled release of drugs in animal or human bodies.

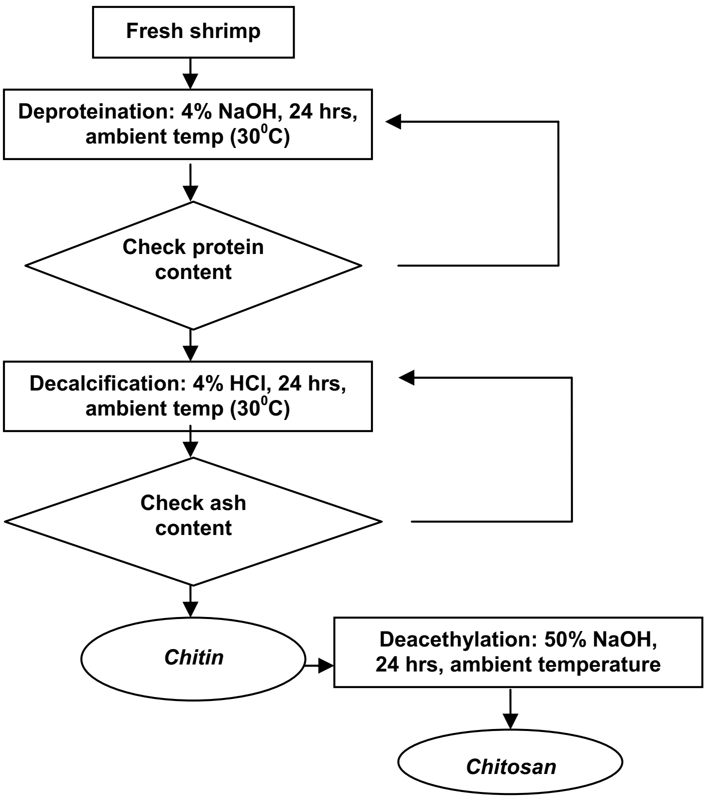


Figure 6.17 Production of Chitin and Chitosan

Table 6.7 Applications of chitin in its original or modified form

Chitin form	Properties used	Applications	References
Micro crystalline chitin	Phosphorylation	Aroma in diet foods	Austin *et al.* (1981)
Micro crystalline chitin	Growth of bifido bacteria	Feed preparation using whey with high lactose content.	Austin *et al.* (1981)
Crossed linked chitin with glutaraldhehyde	Adsorption natural flocculants	Removal of cupric ions	Koyama and Taniguchi (1986)
Pure form chitin	Solid support	Immobilization of enzymes papian, phosphate, trypsin, lactase	Brzeski (1987)
Dissolved chitin	Membrane formation	Osmosis, ultrafiltration, reverse osmosis, desalinization.	Brzeski (1987)
Chitin flakes	Conditioning agent	Activated sludge, trap pollutants, insecticides, pesticides	Brzeski (1987)
Partially deacethylated chitin (PDC)	Antistatic and soil repellent	Textiles, reduce shrinking	Brzeski (1987)
Chitin flake, sponge and ointment (polyethylene glycol)	Anti fungal agent, activate cell growth	Wound healing on different parts of body	Hirota *et al.* (1995) Sathirakul *et al.* (1995)

It appears that the production of chitin and chitosan from shrimp or crustacean shells will yield several benefits to human and the environment. Further research in this aspect is needed to develop more cost-effective production methods, which should enhance the properties of chitin and chitosan and broaden their uses and applications.

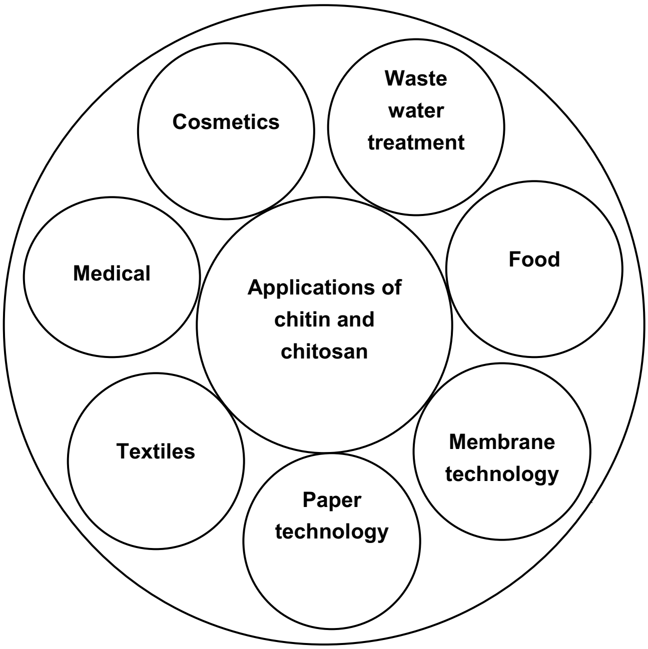


Figure 6.18 Application of Chitin and Chitosan

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6.10 EXERCISES

6.1 What are the health problems associated with fish farming in wastewater-enriched pond? What would you suggest to solve these problems?

6.2 Calculate the ammonia concentration in a water sample at pH = 8 and NH_3-N + NH_4-N = 10 mg/L. The following equilibria exist:

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$$

$$K_b = \frac{[NH_4][OH^-]}{[NH_3]} = 1.76 \times 10^{-5} \quad \text{(at 25°C)}$$

$$K_w = [H^+][OH^-] = 10^{-14} \quad \text{(at 25°C)}$$

The U.S. Committee on Water Quality Criteria (1972) has recommended that, to safeguard fish, no more than 0.02 mg/L NH_3 be permitted in receiving waters. Does the ammonia concentration in the above calculation meet the Criteria? If not, suggest methods to make the water safe for the fish.

6.3 Compare the advantages and disadvantages of applying commercial fish meal or cattle manure into fish ponds for the purpose of raising Tilapia for use as animal feed.

6.4 You are to visit a commercial fish farm and obtain the following information:

- fish species and stocking density
- type and amount of fish meal being fed to the fish ponds
- productivity of the fish ponds in unit of kg fish/(ha-yr)

From the above data, estimate the organic loading rate (in kg BOD or COD/ha-day) and the percent fish mortality. Also suggest some improvements, if any, to be made to increase the fish productivity in this farm.

6.5

a) A small community produces septic tank sludge (septage) with the following characteristics:

Quantity	= 10 m^3/day
COD	= 20000 mg/L
Total Kjeldahl N	= 1800 mg/L

This septage is to be used to feed to fish ponds to produce Tilapia with a mean weight of about 30 g for use as animal feed. Three fish harvests are planned annually, with 100 days for fish culture and 3 weeks for pond maintenance. Suppose Tilapia can tolerate DO concentration at dawn of no lower than 1.5 mg/L. What should be the highest COD loading to be applied to the septage-fed fish pond(s)? Also determine the total land area required, stocking density, the number of fingerlings needed and the expected fish output for each cycle (120 days).

b) Suppose that for efficient fish harvesting, the pond water is to be drained out, what should be done with this pond water and the pond sediment that needs to be removed?

6.6 What are the fish species that the people in your country like to eat? Would the people mind if the fish sold in the market are reared in waste-fed ponds? Suggest methods to make the waste-grown fish more acceptable to the people.

6.7 An agro-industrial factory produces wastewater with the following characteristics

Flow rate	= 10 m^3/day
COD	= 5,000 g/m^3
$NH_3 + NH_4^+$	= 10 g/m^3

The factory plans to apply this wastewater to a fish pond to raise tilapia for use as animal feed (mean individual fish weight = 30 g)

a) If, to maintain satisfactory D.O. levels at dawn, the organic loading rate to be operated in the tilapia pond is 100 kg COD/(ha-day), determine the required dimension (length × width × depth) of the tilapia pond, appropriate fish stocking density and fish productivity in kg/year (if this tilapia is to be harvested 2 times per year). Data on fish productivity is given in Figure 6.11.

b) To avoid fish toxicity, the NH_3 concentration in the fish pond water should be less than 1 mg/L. If due to the algal-bacteria symbiotic reactions, the pH of the fish pond water becomes 9 at 3 pm., determine whether there will be NH_3 toxicity to fish or not. If so, suggest method to alleviate this problem. Figure 6.9 shows the effects of pH on NH_3 + NH_4^+ concentrations.

7

Aquatic weeds and their utilization

Aquatic weeds are prolific plants growing in water bodies, which can create a number of problems due to their extensive growth and with high productivity. Since they exhibit spontaneous growth, they usually infest polluted waterways or water bodies, reducing the potential uses of these watercourses. The problems of aquatic weeds have been magnified in recent decades due to human's intensive uses of the natural water bodies and pollution discharges into these water bodies. Eradication of the aquatic weeds has proved impossible and even reasonable control is difficult. However, turning these aquatic weeds into productive uses such as in wastewater treatment, in making compost fertilizer, and as human food or animal feed, etc., some of the problems created by aquatic weeds may be minimized and yielding some incentives for the people to harvest the aquatic weeds more regularly.

7.1 OBJECTIVES, BENEFITS, AND LIMITATIONS

7.1.1 Objectives

The main purposes of using aquatic weeds in waste recovery and recycling are for waste stabilization and nutrient removal, and conversion of the harvested weeds into productive uses. Aquatic weeds provide a medium for bacteria to be attached and grow at their roots and stems, to stabilize the waste. The presence of weeds in the aquatic medium and subsequent harvesting enable the nutrient removal from the wastewater. Even though stabilization of waste is a slow process in aquatic systems, the removal efficiency is high and can produce an effluent superior or comparable to that of any other treatment systems. The productive uses of aquatic weeds are given below.

7.1.2 Benefits

Aquatic weeds can be used, directly or after processing, as soil additives, mulch, fertilizer, green manure, pulp and fibre for paper making, animal feed, and human food, organic malts for biogas production and for composting. If properly designed, the operation and maintenance of the aquatic weed system does not require highly skilled manpower.

7.1.3 Limitations

Land requirement

Waste treatment with aquatic weeds requires large area of land at reasonably low cost. This will become one of the major limitations in urban areas, but in rural areas this will not be a problem.

Pathogen destruction

The reliability of an aquatic system with regard to pathogen destruction is low because the inactivation mechanism is natural die-off during long detention time, and some of the aquatic plants will provide suitable condition for the survival of pathogenic microorganisms.

End uses

Most of the end use of aquatic weeds are for agricultural and livestock rearing purposes. So the aquatic weed systems are suitable for rural areas.

However, interests in the beneficial uses of aquatic weeds are increasing worldwide and the methods of aquatic weed utilization, as listed in sections 7.5 and 7.6, are being applied in several countries with positive results.

7.2 MAJOR TYPES AND FUNCTIONS

Aquatic weeds may be divided into several life forms, a somewhat arbitrary separation since there are plants, which may change their life form depending on their stage of growth or on the depth of water. The major types are: submerged, floating and emergent weeds, as shown in Figures 7.1, 7.2 and 7.3, respectively. The most common plants and their scientific names are given in Table 7.1.

7.2.1 Submerged type

Weeds that grow below the water surface are called submerged. Often they form a dense wall of vegetation from the bottom of the water surface. Submerged species can only grow where there is sufficient light and may be adversely affected by the onset of factors such as turbidity and excessive populations of planktonic algae, which decreases the penetration of light into the water. Thus these species are not effective for effluent polishing.

7.2.2 Floating type

According to Reimer (1984), there are two subtypes of floating weeds, i.e. floating unattached and floating attached. The roots of floating unattached plants hang in the water and are not attached to the soil. The leaves and stems are above the water thus receiving sunlight directly. The submerged roots and stems serve as habitat for the bacteria responsible for waste stabilization, the aquatic weeds that cause some of the most widespread and serious problems fall into this type. As these plants are unattached, populations of the plants are seldom permanent and, if space permits, are liable to be moved by wind and water currents or, if confined in one place, initiate the accumulation of organic matter which decreases the depth of water until it is sufficiently shallow for the establishment of emergent swamp vegetation. Thus they are essentially primary colonizers in aquatic ecosystems.

Floating attached plants have their leaves floating on the water surface, but their roots are anchored in the sediment. The leaves are connected to the bottom of petioles (e.g. water lilies, Figure 7.2 f and g), or by a combination of petioles and stems.

7.2.3 Emergent Type

These are rooted weeds that extend above the water surface. Such attached aquatic plants usually grow well in a stable hydrological regime and are less likely to be a problem in situations where rapid or extensive fluctuations in water level occur. Specialized communities of emergent species may develop on a substratum of floating aquatic plants, especially where stands of the emergent species are particularly stable.

There is frequently a pronounced zonation of different life forms to different depths of water (Figure 7.4). The emergent type normally grows in shallow water and the submerged type in deeper water in which light can still penetrate to the bottom. The floating types are independent of soil and water depth.

Like any other plants, aquatic weeds require nutrients and light. The major factors governing their growth are:

- Ambient temperature
- Light
- Nutrients and substrate in the water
- pH of water
- Dissolved gases present in the water
- Salinity of the water
- Toxic chemicals present in the water
- Substrate and turbulence
- Water current in rivers and lakes
- River floods
- Morphology of bodies of water

While the above-mentioned factors modify the composition of the plant communities, they are in turn modified by the latter. This results in constant interaction between the plants and the environment. Furthermore, the environmental factors also interact with one another, resulting in a complex relationship between the environmental factors and the aquatic weeds.

Table 7.1 Types and common names of aquatic weeds

Types	Common name	Botanical name
Submerged	Hydrilla	*Hydrilla verticillata*
	Water milfoil	*Myriophyllum spicatum*
	Blyxa	*Blyxa aubertii*
Floating	Water hyacinth	*Eichhornia crassipes*
	Duckweeds	*Wolfia arrhiga*
	Water lettuce	*Pistia stratiotes*
	Salvinia	*Salvinia spp.*
Emergent	Cattails	*Typha spp.*
	Bulrush	*Scirpus spp.*
	Reed	*Phragmites communis*

Figure 7.1 Submerged aquatic weeds, hydrilla (*Hydrilla verticillata)*

7.3 WEED COMPOSITION

7.3.1 Water content

Aquatic weeds have high water content, in general ranging from 85-95%. It varies from 90-95% for floating species, 84-95% for submerged species, and 76-90% for emergent species. The differences amongst the various life forms can be correlated to some extent with the amount of fiber present in the plant. Water supports the weight of submerged aquatic plants, so they do not develop fibrous stems. Floating plants and emergent plants require more skeletal strength in their aerial parts and so have more fiber than most of the submerged plants.

The low level of dry matter has been the major deterrence to the commercial use of harvested weeds. In order to obtain 1 ton of dry matter, 10 tons of aquatic weeds must be harvested and processed. For water hyacinth, which usually contains only 5% dry matter, 20 tons must be harvested and processed just to obtain 1 ton of dry matter. By comparison, terrestrial forages contain 10-30% solids, and therefore, are cheaper to harvest.

Figure 7.2 Floating aquatic weeds, water hyacinth (*Eichhornia crassipies)*

Figure 7.3 Emergent aquatic weeds, cattail

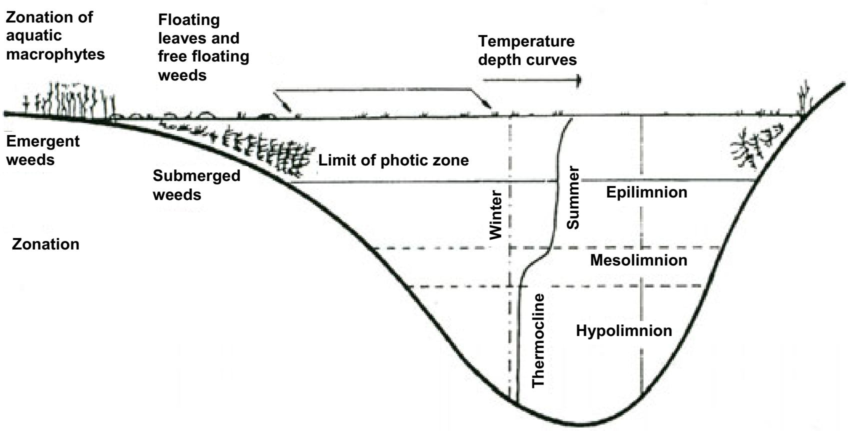

Figure 7.4 A diagrammatic representation of a lake showing zonation of aquatic weeds, the photic zone, and thermal stratification (adapted from Mitchell 1974; ©UNESCO 1974; reproduced by permission of UNESCO)

7.3.2 Protein content

For most species of aquatic weeds about 80% of the total-N is in the form of protein. Aquatic weeds contain 8-30% of crude protein (on a dry-matter basis) - a range similar to that found in terrestrial crops. The considerable variations in crude protein content are due to both seasonality and environment. The crude protein content of *Typha latifolia* decreased from 10.5% in April to 3.2% in July (Boyd 1970) and that of *Justicia americana* from 22.8% in May to 12.5% in September (Boyd 1974). In addition, the crude protein content of *Typha latifolia* from different sites varied from 4.0-11.9% (Boyd 1970), and that of water hyacinth grown on a stabilization pond was 14.8% compared to 11.3% in samples from a lake (Bagnall *et al.* 1974). This indicates that the crude protein content increases as the nutrient content of the water in which the plant is grown increases. According to Wolverton and McDonald (1976b), the crude protein of water hyacinth leaves grown in wastewater lagoons average 32.9% dry weight, which is comparable to the protein content of soyabean and cotton seed meal. This value is more than two times the maximum crude protein content of water hyacinth reported by Bagnall *et al.* (1974). Duckweeds have a crude protein content over 30% and have a better spectrum of amino acids as regards to lysine and methionine than the other plants (Oron *et al.* 1986).

Although the protein content of various aquatic weeds differs greatly, the amino acid composition of the protein is relatively constant, nutritionally balanced, and similar to many forage crops. But the levels of methionine and lysine - generally considered as the limiting amino acids in plant proteins - are lower than in terrestrial crops (Boyd 1970). Additional information on protein content of aquatic weeds is given in section 7.6.2.

7.3.3 Mineral content

The ash content of aquatic weeds varies with location and season. Sand, silt, and encrusted insoluble carbonates from the water account for much of the mineral content. Although silt can be washed off the plants, in practice it represents part of the chemical composition of the harvest. The amount of minerals varies from 15-25% of the harvest (dry weight), depending on the waterway's chemical content and turbidity (Table 7.2).

The amounts of phosphorus, magnesium, sodium, sulfur, manganese, copper and zinc in aquatic weeds growing in nature are similar to those in terrestrial plants. However, aquatic plants are often richer in iron, calcium and potassium than land forages, and some species are known to concentrate such minerals. Elements can be exceptionally high in aquatic plants grown in sewage or industrial and agricultural wastewaters. In fact, the low palatability of aquatic weeds to livestock has been attributed to a high mineral content (see section 7.6).

7.3.4 Miscellaneous

Some aquatic plants have carotene and xanthophyll pigment concentrations that equal or exceed those of terrestrial forages such as alfalfa. These pigments are important ingredients in poultry rations.

Pesticides have been found in aquatic plant samples collected when the waterway has been recently treated with herbicides or insecticides. Also, traces of cyanide, oxalate, and nitrate have been found. However, no evidence of toxicity to mice, sheep or cattle has yet been found in water hyacinth or hydrilla samples.

7.4 PRODUCTIVITY AND PROBLEMS CAUSED BY AQUATIC WEEDS

Aquatic weeds, especially rooted, emergent species and floating species are some of the most productive freshwater ecosystems. Typical values for the net production of different types of aquatic vegetation from fertile sites (recorded in terms of unit weight per unit area of the earth's surface per unit time) are as follows (Westlake 1963): lake phytoplankton 1-8, submerged weeds 3-18, and emergent weeds 27-77 and floating weeds 35-90 tons of dry organic matter/(ha-yr). At that time, the highest net productivity recorded was for sugar cane, 85 tons dry matter / (ha-yr).

The productivity of submerged weeds is usually low because the water reflects and absorbs some of the incident light, coloured substances in the water absorb light, and the diffusion of carbon dioxide in solution is slow compared to its diffusion in air. The presence of phytoplankton in the water column also reduces the light available for submerged plants, and, in eutrophic waters may be dense enough to cause the elimination of aquatic weeds. On the other hand, emergent weeds are particularly productive since they make the best use of all three possible states, with their roots in sediments beneath water and with the photosynthetic parts of the plant in the air. The surrounding mud around the roots may be a good source of soluble nutrients, which can diffuse to the roots via the pore water in the sediments. Light and carbon dioxide are more readily available in the air than in water. Thus, they make the best of both aquatic and terrestrial environments.

Table 7.2 Chemical composition of water hyacinth taken from several natural Florida, USA, locations (composition reported as percentage dry weight)

Origin	Ash	C	N	C/N ratio	P	K	Ca	Mg	Na
Lake Istokpoga (Sebring)	24.4	18.0	1.08	16.7	0.14	1.00	0.73	0.38	0.15
Lake Eden Canal (SR 532)	19.4	28.8	0.86	33.5	0.09	1.95	0.46	0.31	0.23
Lake Thonotosassa	23.0	23.0	1.17	19.7	0.33	3.35	1.49	0.29	0.21
Waverly Creek (SR 60)	25.0	33.1	2.26	14.6	0.56	3.10	1.58	0.50	0.37
Arbuckle Creek	23.4	34.9	1.90	18.4	0.23	3.35	1.06	0.49	0.28
Lake Tohopekaliga (Kissimmee)	21.7	34.0	1.69	20.1	0.60	4.70	1.56	0.71	0.53
Lake Monroe (Sanford)	20.4	32.5	2.86	11.4	0.59	5.55	1.73	0.54	0.83
Duda Canal No 1 (Bella Glade)	20.3	39.1	1.30	30.1	0.13	3.80	1.99	0.60	0.48
St. Johns River (Astor)	20.1	36.4	2.33	15.6	0.51	6.50	1.43	0.51	0.63
W. R. Grace landfill (Bartow)	19.0	36.4	1.86	19.6	0.59	2.72	1.99	0.56	1.54
Ponce de Leon Springs	18.5	37.5	1.74	21.5	0.33	5.40	2.34	0.50	0.47
Waverly Creek (SR 540)	18.5	38.1	1.76	21.6	0.32	4.85	1.45	0.55	0.67
Duda Canal No 2 (Bella Glade)	17.5	37.8	1.66	22.8	0.15	4.70	2.28	0.69	0.57
Lake Alive (North of Florida)	17.3	38.6	1.17	33	0.40	3.66	2.41	0.69	0.40
Lake Apopka (Monteverde I)	15.8	38.8	1.22	31.8	0.14	4.26	2.07	0.54	0.41
St. Johns River (Palatka)	15.8	38.0	1.82	20.9	0.16	3.44	1.83	0.73	0.86
Lake George	15.4	40.2	1.48	27.1	0.21	3.21	1.91	1.86	1.24
Lake Apopka (Monteverde I)	14.9	39.8	1.36	29.3	0.09	4.08	1.96	0.60	0.21
Lake East Tohopekaliga (St. Cloud)	14.7	37.2	1.08	34.5	0.23	2.90	1.19	0.51	0.53
Mean	19.2	34.9	1.61	23.3	0.31	3.81	1.66	0.56	0.56
Standard Deviation	3.2	5.9	0.50	7.0	0.18	1.30	0.53	0.14	0.36

Floating weeds are also equally or more productive than emergent plants as they can be moved with winds and currents and their productivity far exceed the biomass yields of many subtropical terrestrial, salt water, and freshwater plants (Wolverton and McDonald 1978).

The growth rate for aquatic weeds can also be expressed as the specific growth rate independent of biomass or the units in which biomass is measured (dry weight). The values can be measured as fractional increase per day or percent increase per day. In 1969, Bock calculated the daily incremental factor using the following formula (Mitchell 1974):

$$N_t = N_0.x^t \tag{7.1}$$

Where:
N_o = initial number of plants
N_t = final number of plants
t = time interval in days
x = daily incremental factor

However, the specific growth rates are generally high at low plant density and decrease as the plant density increases.

Growth of aquatic weeds can also be reported in terms of doubling time, the time taken for the material present to double itself (or $N_t / N_o = 2$). In 1974, Gaudet while working with *Salvinia minima* and *S. molesta* under standardized culture conditions calculated the doubling time using the following formula (Mitchell 1974):

$$\text{Doubling time} = \frac{ln\, 2}{(ln\, N_t - ln\, N_0)/t} \tag{7.2}$$

The notations are the same as used in Equation 7.1.

Under favorable conditions, the area doubling time for water hyacinth ranges between 11-18 days, depending on the weather. Mitchell (1974) obtained doubling times for *S. molesta* of 4.6-8.9 days in culture solutions in the laboratory, compared to 8.6 days on Lake Kariba, Africa. Bagnall *et al.* (1974) and Cornwell *et al.* (1977) both reported doubling times of 6.2 days for water hyacinth grown on a stabilization pond receiving secondarily treated effluent. The variation of doubling times reported in the literature is due to the effects of weather, nutrients, growing season and plant density.

Knowledge of area doubling time is useful to determine the frequency of plant harvesting and the amount of harvested plant biomass to be further processed. Because plants grow and die relatively quickly under tropical conditions, harvesting of these plants from the water body needs to be done properly to prevent plant decay and impairment of the water quality. Application of the area doubling time in plant harvesting is given in Examples 7.3 and 7.4

Due to their prolific growth, aquatic weeds can cause many problems, the major ones being listed below:

- Water loss by evapo-transpiration,
- Clogging of irrigation pumps and hydroelectric schemes,
- Obstruction of water flow (Figure 7.5),
- Reduction of fish yields and prevention of fishing activities,
- Interference with navigation,
- Public health problems, as aquatic weeds can become the habitat for several vectors,
- Retardation of growth of cultivated aquatic macrophyte crops, e.g., rice and water chestnut,
- Conversion of shallow inland waters to swamps.

The problem of aquatic weed infestation is global but is particularly severe in the tropics and subtropics where elevated temperatures favor year round or long growing seasons, respectively. The annual world cost of attempts to control aquatic weeds is nearly US$2,000 million (Pirie 1978).

Currently the most serious problems associated with aquatic weeds are caused by water hyacinth, which is now more or less ubiquitous in warm waters. In the tropical and subtropical southeastern USA, there is a serious water hyacinth problem. In Florida alone more than 40,000 ha are covered by the plant, despite a continuous control program costing US$10-15 million annually. Subsistence-level farmers in the wet lowlands of Bangladesh annually face disaster when rafts of water hyacinth weighing up to 270 tons/ha are carried over their rice paddies by floodwaters. The plants remain on the germinating rice and kill it as the floods recede. In India, large irrigation projects have been rendered useless by plants that block canals, reducing water flow significantly.

Water hyacinth came originally from South America where it causes few problems since it is kept in check by periodic flooding and changes in water level. The plants are flushed out as a water body enlarges due to seasonal flooding and as the floods subside the aquatic plants are left stranded on dry land above the receding water level (Mitchell 1976). The absence of natural enemies in their new environments has often been implicated as a casual factor in the rampant growth of water hyacinth and other aquatic weeds. Therefore, the absence of periodic flooding in artificial lakes and irrigation schemes may be the major contributing factor to the development of aquatic weed problem. This problem is further exacerbated by eutrophication from human, animal and agro-industrial wastes, and agricultural runoff (Figure 7.5). As new lakes and irrigation schemes are developed, the newly submerged soil and vegetation provides a rich source of nutrients favouring aquatic plant growth (Little 1968).

Another problematical aquatic weed is the fern *Salvinia molesta*. On Lake Kariba, Africa, the largest man-made lake in the world, there was a steady increase in the area of the lake colonized by the fern following the closure of the dam in 1959, when 1,000 km^2 or 2.5% of the lake's surface was covered. Since 1964 (two years after the dam was opened in 1962) the area covered has fluctuated between 600 and 850 km^2 and is limited mainly by wave action that has increased as the lake has reached full size (Mitchell 1974). The same species is a serious threat to rice cultivation throughout western Sri Lanka and covers about 12,000 ha of swamp and paddy fields (Dissanayake 1976).

Figure 7.5 A drainage canal in Colombo, Sri Lanka, filled with water hyacinth, *Eichhornia crassipes*

7.5 HARVESTING, PROCESSING AND USES

Harvesting aquatic weeds from the waterways and utilizing them to defray the cost of removal is one of the most successful approaches to aquatic weed management. It results in weed-free waterways while providing an extensive vegetation resource. This is especially advantageous in developing countries where forage and fertilizer are in short supply.

The removal and recycling of nutrients and other components is done by harvesting, processing and utilizing the aquatic plants in which the nutrients are collected. The whole process is shown by a simple schematic diagram given below:

AQUATIC WEEDS → HARVESTING → PROCESSING → PRODUCT → USES

A complete network of the possible processes used to convert aquatic weeds to a variety of products is shown in Figure 7.6. Harvesting and chopping are precursors to all of the other processes and all of the products. The chopped plants can be applied directly to land, composted to stabilize and reduce mass, digested to produce methane, pulped to produce paper, or pressed to reduce moisture content and produce a highly reactive protein-mineral-sugar juice. The juice can be separated to recover a high quality food-feed protein-mineral concentrate or digested to produce methane. The pressed fibers may be ensiled with appropriate additives or dried to produce a granular feed component.

This section deals with all uses of harvested weeds, except the use of weeds as food and feed, which is dealt separately in section 7.6 (Food Potential of Aquatic Weeds).

7.5.1 Harvesting

Harvesting can be accomplished manually or mechanically, depending on the amount of weeds to be harvested and the level of available local technology.

Large floating plants such as *Eichhornia crassipes* and *Pistia stratiotes* can be lifted from the water by hand or with a hayfork. Smaller floating plants such as *Lemna* or *Azolla* can best be removed with small mesh sieves or dip nets. Submerged plants can be harvested by pulling rakes through the under-water plants. Emergent and floating-leaved plants can be cut at the desired height with knives, or in areas with loose bottom soil, pulled by hand. One man can harvest 1,500 kg or more of fresh weight of plants per day from moderately dense stands of most species.

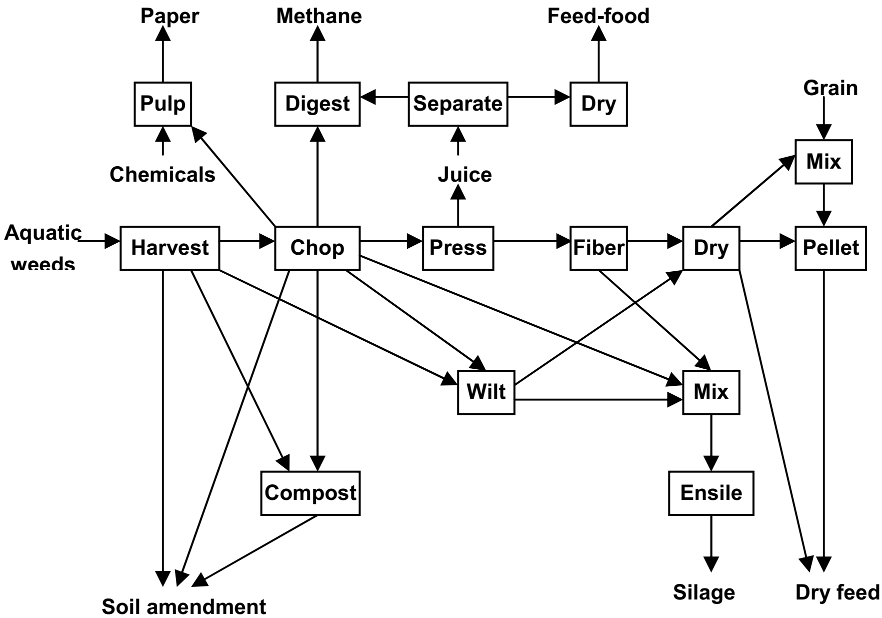

Figure 7.6 Different end products of harvested aquatic weeds (from Bagnell 1979; reproduced from the permission of the American Society of Agricultural (Engineers)

Large-scale harvesting is done with the help of various mechanical devices mounted on boats or barges. Harvesting can be carried out from a site at the water's edge or with a self-propelled, floating harvester. Shoreside harvesting requires that the plants float to the harvester. Rooted species must be uprooted or mowed and then moved to the harvester by boat or by wind and current. Plants can then be lifted from the water by hand, crane, mechanical conveyor, or pump. On the other hand, mobile harvesters sever, lift, and carry plants to the shore. Consisting of a large barge on which a belt conveyor and a suitable cutting mechanism are mounted, these harvesters are mostly intended for harvesting submerged plants. Nowadays, some harvesters have also been designed to harvest floating plants or the mowed tops of submerged plants.

Harvesting frequency has to be chosen depending on the initial area of coverage of the plants (or stocking density) and the area doubling time. For example, if a plant is stocked to cover half of the pond area harvesting may be done to remove half of the plants at every interval of doubling time. Plants such as duckweeds which are easily piled up due to wind or could not compete with algae for space and food have to be stocked at higher initial stocking density to prevent algal blooms.

After the weeds have been harvested, their handling is another problem. Because of their enormous water content (which results in very low bulk density), the weeds are exceedingly difficult to handle and their transportation is very expensive. Thus, choppers are often incorporated into harvesting machinery designed for aquatic weeds. Chopping makes the plants much easier to handle and reduces their bulk to less than a fourth of the original volume, greatly simplifying transportation, processing, and storage.

The energy cost of combined harvesting / chopping amounts to about 0.34 kWh/ton and the economic cost to about US$0.14/ton of fresh plants (Bagnall 1979).

7.5.2 Dewatering

Because harvested or chopped aquatic weeds contain 80-95% water, they should be dewatered prior to being used as animal feed or for other purposes. Although sun drying can be employed, this must occur so rapidly that mold and decay do not ruin it, and this practice is not possible all year round.

About half the moisture is on the surface and some is loosely contained in the vascular system. This water can be removed relatively easily by lightly pressing the plant. The squeezed out water contains only about 2% of the plant solids and often can be returned directly to the waterway without causing pollution. Even with half the water removed, aquatic vegetation is still much wetter than terrestrial grass. In order to reduce the moisture further, heavier pressing is required. This process can remove about 70% of the water content and yielding a product that is comparable to terrestrial forage grasses in moisture content.

Depending on plant species, process design and operating conditions, the water removed can carry with it 10-30 percent of the plant's solid matter, 15-35% of the protein, and up to 50% of the ash (for the most part, silt and mineral encrustations caught on the plants). Roller, belt, cone and screw presses are the different types commercially available to dewater weeds, but they are usually in heavy, durable designs that are unnecessarily complex and cumbersome for pressing aquatic vegetation. Lightweight experimental screw presses (suitable for developing countries) have been designed. For example, a small screw press of a simple design has been constructed at the University of Florida, USA (NAS 1976). With its 23 cm bore, this press weighs between 200-250 kg. Complete with a power plant, it can be carried by a truck, trailer or barge to remote locations, and can press 4 tons of chopped water hyacinth per hour. Such presses are compatible with a program of manual harvest and with the small-scale needs for animal feed in rural areas in developing countries (in addition, these presses can be manufactured locally). Estimates of aquatic weed pressing costs range from US$5.0 to US$10.0/ton of dry matter (depending on machine cost, machine use, production rate, amortization time and labour costs) (NAS 1976; Bagnall 1979; Bagnall *et al.* 1974).

In some arid climates solar drying may be feasible, either by exposing a thin layer of the plants to the sun or by more sophisticated solar collector-heat transfer systems. In the U.S., a solar drying system for aquatic weeds was constructed at the National Space Technology Laboratories. Depending on the weather, it is capable of drying 15-17 tons of newly harvested water hyacinth in 36-120 hours (Figure 7.7). Drying of the aquatic weeds with conventional fuel-heated air is economically impractical because of the high moisture content.

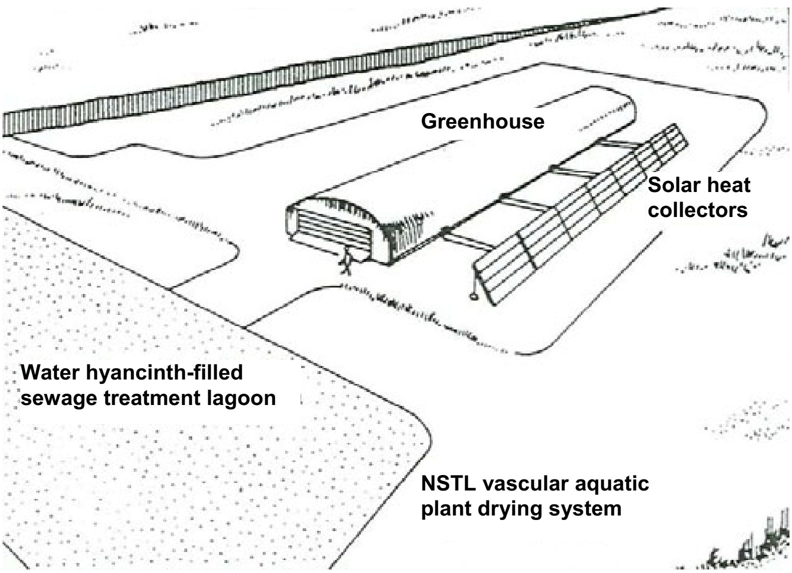

Figure 7.7 Solar energy being harnessed to dry aquatic weeds at the National Space Technology Laboratories (NSTL) near Bay St. Louis, Mississippi (NAS 1976). Note: this system is connected to a lagoon full of water hyacinth growing in sewage effluent.

7.5.3 Soil Additives

Mineral fertilizers are expensive for many farmers in developing countries, yet there is a greater need now than ever to increase food production. As an alternative, the 1974 World Food Conference and, more recently, the Food and Agricultural Organization (FAO) of the United Nations have stressed the urgency of reassessing organic fertilization. This includes the possible ways in which aquatic weeds can be used as organic fertilizers, namely, as mulch and organic fertilizer, ash, green manure, compost, or biogas slurry.

Mulch and organic fertilizer

Mulching involves the laying of plant material on the surface of the soil to reduce evaporation and erosion, to smother weeds and for temperature control. Both sand and clay soils need conditioning to make them productive. Working plant material into the soil improves its texture, and also, by acting as manure, improves the nutrient content. Several species of aquatic weeds that can be used as manure are *Pistia stratiotes*, *Hydrilla verticillata*, *Salvinia spp., Eichhornia crassipes* and *Azolla* (Frank 1976; Gopal and Sharma 1981; Gupta and Lamba 1976; Little 1968).

The high moisture content of aquatic weeds makes them suitable as mulch. But the time and labour involved in harvesting and distributing even sun-dried material would preclude such a use, except on a small scale adjacent to the watercourse in which the aquatic weeds occur.

Ash

Although it has been suggested that the ash of water hyacinth can be used as a plant fertilizer, some reasons showing that it is not feasible are:

- Burning of the plant to ash results in the loss of nitrogen and organic matter, which reduces the fertilization potential of the plant.
- Burning of the plant requires previous drying which involves additional labour and expenditure and is restricted to dry days of the year, while growth and distribution of the weeds is most profuse in wet months.
- Ash needs immediate bagging and storing in order to prevent it from being washed away by rain or carried away by wind.

Thus, the cost of labour and energy required to obtain ash from aquatic weeds seems to far exceed the value of the ash obtained as a fertilizer (Little 1968).

Green manure

Green manure, in a strict sense, is plant matter cultivated for its fertilizer value to other crops. However, certain species of aquatic weeds that grow wild in rice fields and are ploughed into paddy, e.g. *Limnocharis flava* and *Sesbania bispinnosa*, are sometimes referred to as green manure. Thus, the distinction between aquatic weeds, which grow wild and are used as manure and fertilizer, and green manure which is cultivated, is not always maintained. Certain types of aquatic weeds are cultivated as green manure or biofertilizers to add nitrogen to the soil, and this practice is useful since it lessens dependence on commercial, inorganic fertilizer.

The cultivation of the fern *Azolla pinnata*, with its symbiotic nitrogen fixing blue-green algae was developed in Vietnam, where it is treated not as a weed but as a valuable crop (Ngo 1984). Edwards (1980) cited a literature that reported that the cultivation of the fern has recently spread to southern China also. In both countries, *Azolla* is produced to fertilize areas of rice and other crops. In northern Vietnam, just before or after rice transplanting, *Azolla* is scattered in the fields at the rate of 4-5 tons/ha, and in January and February it grows along with the rice. During this time, when the mean daily air temperature is 16-17 °C, the paddy is young and available solar radiation and nutrients allow *Azolla* to grow normally, with a result that it completely covers the surface of the water. Towards the end of March, when the temperature rises to 22-24°C, the paddy has grown up and shades most of the surface, resulting in the death of *Azolla* and release of P and K and newly acquired nitrogen to the paddy. The *Azolla* produces about 18 tons of fresh material/ha, and assimilates more than 100 kg N/ha in the 3-4 months growing period. A negligible portion of the fixed nitrogen is released when *Azolla* is growing and it becomes available only on the death of the plant.

Before being applied to agricultural lands and fields, *Azolla* is produced in small, special field where it receives appropriate fertilization and care. In these fields the *Azolla* biomass can double every 3-5 days in good weather. A one-hectare field fully covered with *Azolla* can produce 1-4 tons of fresh biomass per day, which contains 2.6-2.8 kg of nitrogen (Ngo 1984). Within 3 months green manure enough to fertilize 4,000 ha of rice fields can be produced from 1 ha of *Azolla* fields. Thus, if year round production of *Azolla* is maintained, one ha of *Azolla* can save 5-7 tons of costly imported chemical fertilizer (ammonium sulfate) per year. Ngo (1984) reported that increase in yield of rice by 30-50%, of sweet potato by 50-100%, and of corn by 30%, have been achieved in fields green manured with *Azolla*.

Because *Azolla* is cultivated as green manure in only limited areas of Asia, there can be management problems in other areas. It grows in abundance in

Japan, India, China, Philippines and Thailand, and tropical strains that grow at 30-35 °C are also found. Because these tropical, local varieties are more heat resistant than the one found in northern Vietnam, they could be developed to become a high-yield and high N-content crop. However, experimentation is needed to determine the full potential of *Azolla* in tropical areas.

Attempts have also been made to use free-living, filamentous, nitrogen-fixing blue green algae to improve fertility of rice fields in Japan and India, but they are still in an experimental stage.

Composting

One of the most promising methods to utilize aquatic weeds is to use them to make compost. Composting requires about 60-70% moisture content (see Chapter 3) and this can be achieved by a few days of wilting in the sun, a great saving over the other drying methods in terms of cost and equipment. They also generally contain adequate nutrients (C/N ratio is between 20 to 30, see Table 7.2), which favour the growth of microbes that produce compost. As previously stated in Chapter 3, the nutrient contents of compost products are usually several times less than inorganic fertilizers. However, when applied to land, about 25-30% of inorganic fertilizer nutrients can leach to groundwater or are not available to the crops. The compost nitrogen is in both organic (or cell biomass) and inorganic forms and is released into the soil gradually, and is thus available throughout the growing season.

Compost can be used as soil conditioner, and as organic fertilizer to raise phytoplankton in fish ponds. The phytoplankton production was found to be directly related to nutrient content of the composts and field trials of using composted water hyacinth to fish ponds resulted in a considerable yield of *Tilapia* (a herbivorous fish) as shown in Table 3.10 (Polprasert 1984).

Pulp, fiber, and paper

Aquatic weeds have found use in producing fibers and pulp for making paper. In Romania *Phragmites communis* (the common reed) has been used to make printing paper, cellophane, cardboard, and various synthetic fibers. Wood pulp is mixed with the reed pulp to increase the tear strength and the density of paper. In addition, the raw weed and pulp mill wastes yield a variety of other products notably cemented reed blocks, compressed fiber board, furfural, alcohol, fuel, insulation material and fertilizer (NAS 1976). For centuries common reed is used to produce peasant crafts, thatching, fences and windbreaks. Its stems are used in basketwork, as firewood, fishing rods, weaver's spool and as mouthpieces for musical instruments.

Cattail is another weed that can be used as a source of pulp, paper and fiber. Its leaves and stems are suitable for papermaking, and the paper obtained is fairly strong but difficult to bleach. Bleaching is however not essential for the production of wrapping paper which is in great demand nowadays. Cattail leaves yield a soft fiber that can be used in mats, baskets, chair seats, and other woven articles. Because they swell when wet, the leaves are good for caulking cracks in houses, barrels, and boats. Studies in Mexico show that woven cattail leaves coated with plastic resins have potential as place mats, building siding, and roof tiles. The resulting product is as strong as fiberglass (NAS 1976).

At the University of Florida, U.S.A., attempts to make paper from water hyacinth were carried out (Bagnall *et al.* 1974). Different pulping materials and conditions were used, but it failed to produce suitable pulp. Reasons for the failure were:

- Very low fiber yield
- Excessive shrinkage of the paper on drying, and subsequent wrinkling
- Brittleness of the paper
- Poor tear properties

Because of the low yield, it was felt that the use of water hyacinth for pulp would not be profitable even if it were delivered to the pulp plant at no cost.

However, dried water hyacinth petioles (leaf stalks) are woven into baskets and purses in Philippines (NAS 1976). In Thailand, water hyacinth leaves are used as a cigar wrapper and for preparing plastic molded materials like furniture, electric insulation board, radio cabinets, and biodegradable pots for flower plants, etc.

Biogas and power alcohol

Chopped water hyacinth alone without dewatering or mixed with animal manure or human waste can be anaerobically digested to produce methane gas (see Table 4.7). Nutrients such as P and K are provided in adequate proportions by water hyacinth. Digestion takes about 10-60 days and requires skilled supervision. Table 7.3 shows the production of several volatile fatty acids during anaerobic digestion of a mixture of cattle dung and water hyacinth. The highest biogas production and methane content were achieved during the digestion period of 30-60 days. It is estimated that water hyacinth harvested from 1 ha will produce approximately 70,000 m^3 of biogas.

Each kg of water hyacinth (dry weight) yields about 370 L of biogas with an average methane content of 61% and the fuel value was about 22,000 kJ/m^3. Temperature has a marked effect on biogas production. The biogas was produced quickly and had higher methane content (69.2%) at 36°C than at 25°C (59.9%). In the same study, Wolverton *et al.* (1975) noted that the rate of methane production is higher in plants contaminated with nickel and cadmium than in uncontaminated plants.

Table 7.3. Production of volatile fatty acids and methane from laboratory fermentation of cattle dung + water hyacinth (1:1 mixing ratio) (Gopal and Sharma 1981).

Duration (days)	**pH**	**Temp. (°C)**	**Volatile fatty acid**	**Average gas production (L/day)**	**Methane (%)**
1-4	7.0-7.5	30	Acetic, propionic and butyric acids	0.95	0
5-13	6.5	27-30	Acetic, propionic and butyric acids and ethanol on 7th day	1.22	3-8
14-28	6.5-7.0	26-29	Acetic, propionic, butyric, isobutyric, valeric and isovaleric acids	0.81	10-60
29-49	7.0	27-28	Propionic acid isovaleric acids	6.01	57-62
50-60	8.0	26-28		4.31	60-64
1-60	8.0-8.5	26-28	From cattle dung alone, acetic, propionic, acid and butyric acids	3.81	50-60

The use of dried water hyacinth as fuel in Indian villages is common. Gopal and Sharma (1981) reported that in 1931, Sen and Chatterjee were the first to demonstrate the possibility of using water hyacinth for generation of power alcohol and fuel gas. They described three methods of utilizing the plant. In one of the methods the plant is saccharified by acid digestion and subsequent fermentation, yielding 100 kg potassium chloride, 50 L ethanol and 200 kg residual fibre of 8,100 kJ calorific value. In another method the plant is gasified by air and steam to produce 1,150 m^3 of gas (equivalent to 150 kJ/m^3), 40-52 kg ammonium sulphate and 100 kg potassium chloride. The gas obtained at 800 °C comprises of 16.6% hydrogen, 4.8% methane, 4.1% carbon dioxide, 21.7% carbon monoxide, and 52.8% nitrogen. The third method employs bacterial fermentation, which produces 750 m^3 gases with a calorific value of 22,750 kJ/m^3. It comprises of 22% carbon dioxide, 52% methane and 25% hydrogen.

The slurry that is the by-product of biogas digestion can be used as organic fertilizer for fish ponds and crops. Field experiments were conducted at the Asian Institute of Technology, Bangkok, in which biogas slurry from four, 3.5m^3 biogas digester units fed with water hyacinth and nightsoil, was added to fish (*Tilapia*) ponds. Extrapolated yields of *Tilapia* were found to be 2800-3700 kg/(ha-year) and this scheme was considered to have potential for rural waste recycling in developing countries (Polprasert *et al.* 1982 and Edwards *et al.* 1987)

These initial studies have generated great interest in biogas production and the recovery of fuel from aquatic weeds, especially for rural areas in developing countries. As many developing countries have an inexhaustible supply of aquatic weeds, this potential energy source deserves further investigation before being commercially exploited.

7.6 FOOD POTENTIAL

Since plants are a starting point of the food chains, they are naturally the source of all food for animals and human. The major pathways involving the use of aquatic weeds in food production are shown in Figure 7.8. The pathways involving composting, mulching, green manuring, ash, and biogas digestion were previously discussed in section 7.5. The discussion on the remaining pathways is presented in this section.

7.6.1 Food for herbivorous fish

There are many species of herbivorous fish that feed on aquatic weeds (Edwards 1980; Mehta *et al.* 1976; NAS 1976), thus converting them to valuable food. They basically fall into three categories:

- Grazers - if they eat stems and foliage.
- Mowers -if they devour the lower portions of aquatic plants and thus cut them down.
- Algal feeders - if they consume algae.

Algal feeders are not considered as they consume single-cell-protein algae, which is outside the scope of this Chapter.

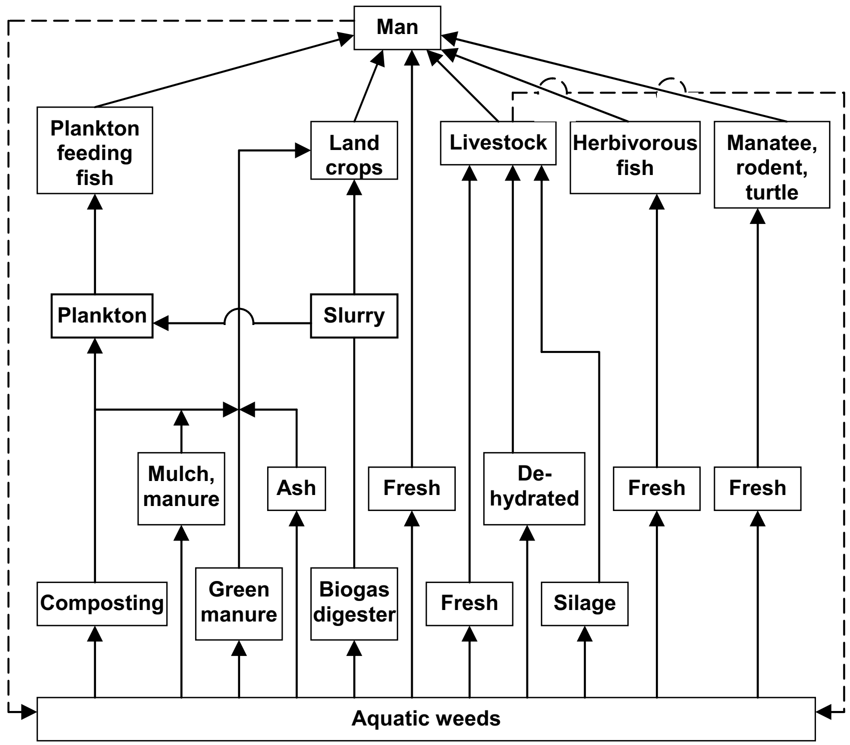

Figure 7.8 A schematic diagram of the major pathways involving aquatic weeds in food production (Edwards 1980) Note: Pathways which may have the greatest potential at present are in a heavier solid line. The broken line indicates that the recycling of livestock and human wastes could play an important role in food production (from Edwards 1980; reproduced by permission of the International Centre for Living Aquatic Resources Management).

Chinese grass carp

The most promising species for the consumption of aquatic weeds is the Chinese grass carp or white amur, *Ctenopharyngodon idella* (Figure 6.2a). It is a fast growing fish that feeds voraciously on many aquatic weeds and grows to weigh as much as 32 kg in mass. It exhibits tolerance to a wide range of temperatures, to low dissolved oxygen level, as well as to brackish water (Mitchell 1974).Being a grazer, the grass carp feeds primarily upon submerged plants, but also eats small floating plants such as duckweed. Submerged weeds consumed by the fish include hydrilla, water milfoil, chara, *Elodea canadensis,* *Potamogeton spp., Ceratophyllum demursum,* and most other submerged plants (Mehta *et al.* 1976; NAS 1976). Overhanging terrestrial plants and bank grasses are consumed when preferred plants are not available. Small fish, less than 1.2 kg, may eat several times their body weight of plant material daily, while large fish consume their body mass daily (NAS 1976). Thus, rapid weed control is achieved if more than 75 fish/ha are present. Stocking rates lower than 75 fish/ha reduce the rate of weed control, but result in larger, more valuable food fish. Grass carp cultured for food yields 164 kg/ha in temperate zones and 1,500 kg/ha in tropical weed infested waters (NAS 1976).

The main difficulty with grass carp is that it is restricted to southern China and does not reproduce in captivity. Recent studies, however, have shown that spawning can be induced by injecting fish pituitary hormone, and in Arkansas, USA, artificial spawning is routine. Another problem is that water hyacinth, *Salvinia*, and other floating weeds that are prevalent in the tropics are not preferred by the grass carp, and it is therefore not a satisfactory agent for controlling them. Neither is it good for controlling tall, hard, emergent aquatic weeds like cattails.

Other herbivorous fish

Besides the grass carp, there are several other species of fish which are used in the dual role of a source of food and as weed-control agents (Edwards 1980; Mitchell 1974; NAS 1976). Of the different species, *Tilapia spp.* is the most commonly used. This tropical lowland fish is common in Africa and Asia, cheap and easy to breed, grows rapidly, and is a voracious feeder of aquatic weeds. Since its flesh is much valued as food, peasant farmers in Africa and Asia culture them in small-scale subsistence and commercial enterprises. Several species of Tilapia fish have been grown in different parts of the world, especially Africa and Southeast Asia.

Two South American species, *Metynnis roosevelti* and *Mylossoma argenteum,* both known as silver dollar, attack a variety of submerged weeds, especially pondweeds. Dense growths of weed are rapidly removed at stocking densities of 1,200 to 2,500 fish/ha. Little is known of their potential yield or value as food, although they occur in large numbers and are sought and relished by people along the Amazon River (NAS 1976).

In addition, a number of other species namely silver carp, tawes, common carp, tambaqui, pirapitinga, American flagfish, and goldfish are being tested for use as weed control agents.

Considerable research is required to identify techniques for their spawning, culturing and managing; their value as food; and their sensitivity to adverse water quality.

Crayfish

Crayfish or freshwater lobsters are an under-exploited food source. They are produced commercially in some European countries, a few areas of U.S.A., and a few tribes in New Guinea use them extensively as their major protein source. Boiled in salt water, they are a delicacy and a gourmet's delight.

There are over 300 known species and a few are exclusively herbivorous. Such varieties appear promising for aquatic weed control and utilization. *Orconectes causeyi*, a species native to the western U.S.A., has been used experimentally for weed control and was effective against pondweeds. *Orconectes nais* has been shown to control aquatic weeds in Kansas, U.S.A. Beyond that little is known about weed control by the herbivorous species of crayfish (NAS 1976). In general, crayfish is thought of more in terms of an available crop associated with aquatic weeds, not as a weed-control agent. Red crayfish *(Procambarus clarkii*) is widely farmed in California and Louisiana in flooded rice fields and lives mainly on aquatic weeds that grow among the rice. The crayfish is too small to eat the rice seedlings at planting, and by the time the crayfish mature, the rice plants are too tall and fibrous to be eaten.

Before crayfish are introduced into new areas, their effect on rice production should be studied carefully. Imported crayfish have become a problem in Japan and in Hawaii where rice paddy dikes have been weakened by their burrowing. Some species of crayfish eat tender shoots of newly germinated rice and should be avoided.

7.6.2 Livestock fodder

Aquatic weeds can be used as feed for livestock after suitable processing. Excessive moisture content in fresh plants restricts the ability of animals to obtain adequate nourishment. The palatability of feed processed from aquatic weeds compares poorly with that of most other conventional feeds. A good feed must contain adequate levels of protein, fat, carbohydrate, vitamins, and mineral nutrients for satisfactory growth. The feed should have fairly low fiber content so that most of the organic matter is highly digestible even to non-ruminant animals.

The proximate compositions of some aquatic weeds which appear suitable as feed are compared with that of alfafa hay, as given in Table 7.4. As can be seen, the composition of dried samples of many species show that they were inferior to alfafa hay for use as livestock feed, but some species were as suitable, or better, than dried alfafa. On average, aquatic weeds contained less crude protein, somewhat more ash and fat and slightly less cellulosic fiber than alfafa. Submerged and floating plants usually have higher values for crude protein and ash than emergent plants. However, the amino acid composition of protein in aquatic weeds is similar to many forage crops (section 7.3b).

Figure 7.9 compares the crude protein content of fresh and dried aquatic weeds to that of fresh and dried alfafa hay. Aquatic weeds compare favorably on a dry mass basis, but not on a fresh mass basis.

Even though nutritional value of aquatic weeds compare favorably (when dried) with alfafa, the cost of artificial drying, grinding, formulating with other feed to improve palatability and pelleting makes the cost of feed from aquatic weeds expensive (Frank 1976; NAS 1976). Nevertheless, water hyacinth can support the growth of livestock, if it is partially dried and properly supplemented, and if the animals are accustomed to it.

None of the feeding tests reported in the literature produced evidence of toxins in aquatic weeds. Potentially toxic substances such as nitrates, cyanides, oxalates, tannins and discoumarins are all present in aquatic weeds, but they also occur in many terrestrial types of forage, so that in general aquatic plants are no more hazardous to livestock than conventional forages (NAS 1976). Boyd (1974), however, reported a concentration of tannins of 10% or more of the dry weight in some species of aquatic weeds, which would greatly impair the digestibility of their protein.

Silage

A promising technique to eliminate the expense of artificially drying aquatic weeds is to convert them to silage (Frank 1976; NAS 1976). Ensiling aquatic weeds could become very important in the humid tropics where it is difficult to sun-dry plants to make hay. According to NAS (1976), water hyacinth silage can be made with 85-90% moisture content since the fiber retains water well and thus the material does not putrefy. But Bagnall *et al.* (1974) found that chopped water hyacinth alone could not be made into silage since it putrefied and that 50% or more of the water had to be pressed from the hyacinth before it could be made into acceptable silage. The aquatic weeds could be wilted in the shade for 48 hours, or chopped and pressed to remove some of the water. Also, since silage is bulky, the silos should be located near the animals and supply of plants.

Table 7.4 Proximate composition (% dry weight) of some aquatic plants and alfafa hay (Boyd 1974)

Species	Ash	Crude protein[a]	Fat[b]	Cellulose[c]
Eichhornia crassipes[d]	18.0	17.0	3.6	28.2
Pistia stratiotes[d]	21.1	13.1	3.7	26.1
Nelumbo lutea[e]	10.4	13.7	5.2	23.6
Nuphar advena[e]	6.5	20.6	6.2	23.9
Nymphoides aquatica[f]	7.6	9.3	3.3	37.4
Potamogeton diversifolius[f]	22.7	17.3	2.8	30.9
Najas guadalupensis[f]	18.7	22.8	3.8	35.6
Ceratophyllum demersum[f]	20.6	21.7	6.0	27.9
Hydrilla verticillata[f]	27.1	18.0	3.5	32.1
Egeria densa[f]	22.1	20.5	3.3	29.2
Typha latifolia[g]	6.9	10.3	3.9	33.2
Justicia americana[g]	17.4	22.9	3.4	25.9
Sagittaria latifolia[g]	10.3	17.1	6.7	27.6
Alternanthera philoxeroides[g]	13.9	15.6	2.7	21.3
Orontium aquaticum[g]	14.1	19.8	7.8	23.9
Alfaalfa hay	8.6	18.6	2.6	23.7

[a] Nitrogen x 6.25.
[b] Ether-extractable material.
[c] Cellulose values are slightly lower than values for crude fibre.
[d] Floating species.
[e] Floating-leaved species.
[f] Submerged species.
[g] Emergent species.

Note: -Each value is the average of 3-15 samples
-All samples represent plants, which were in lush, green stage of growth.

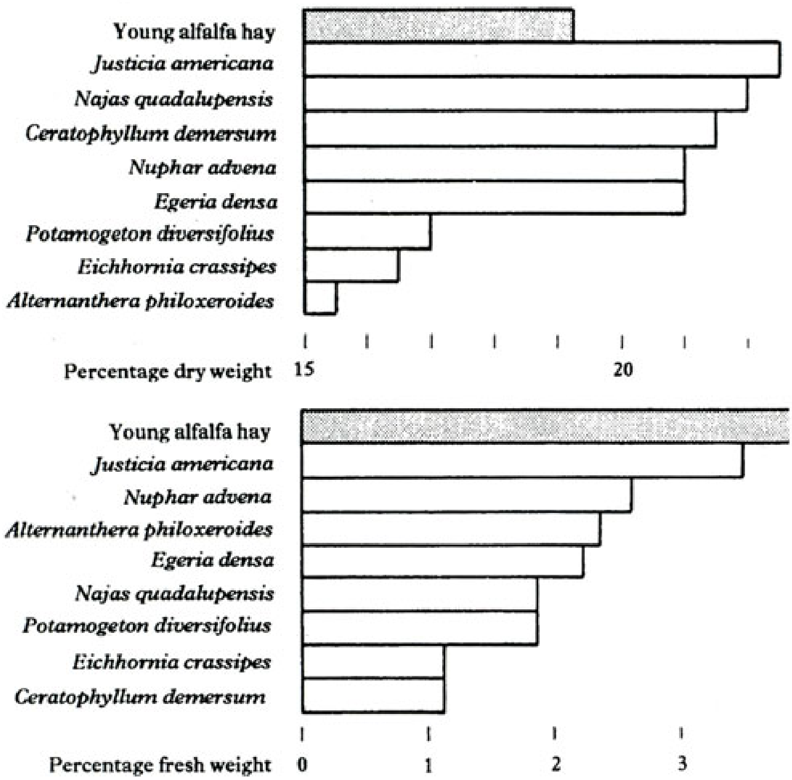

Figure 7.9 Comparison of the percentage crude protein of young alfalfa hay with the crude protein content of eight aquatic weeds (Boyd 1974; © UNESCO 1974; reproduced by permission of UNESCO)

To make silage, the aquatic weeds is chopped into small pieces and firmly packed into a silo to produce oxygen-free conditions. Putrefaction is avoided since material is preserved by organic acids such as lactic and acetic acids, which are produced during anaerobic fermentation. The process takes about 20 days, after which the pH falls to about 4. Aquatic plants are often low in fermentable carbohydrates so it is necessary to add sugar cane, molasses, rice bran, wheat middlings, peanut hulls, cracked corn, dried citrus pulp, etc. to avoid putrefaction. Silage made from water hyacinth alone is not acceptable to livestock, but the quantity consumed by cattle increases as the level of added carbohydrate is increased, although the addition of sugar cane molasses alone does not improve acceptability. The most acceptable water hyacinth silages to cattle contain 4% dried citrus pulp or cracked yellow dent corn (Bagnall *et al.* 1974).

Silage treated with formic acid as a preservative (about 2 L acid/ton pressed water hyacinth) is usually superior to untreated silage as cattle feed. Studies with other organic acid preservatives, e.g. acetic and propionic acids, have also been successful.

Added carbohydrate also functions as an absorbent material that is necessary because of the high water content of the weed. If highly absorbent additives could be found, this may eliminate the need for preliminary dehydration (NAS 1976). In this respect, the use of chitin as an absorbent additive (section 6.8) appears promising, but cost effectiveness of this application needs to be studied on a case-by-case basis.

Human food

Aquatic plants can provide three types of food: foliage for use as a green vegetable; grain or seeds that provide protein, starch or oil; and swollen fleshy roots that provide carbohydrate, mainly starch. There are more than 40 species of aquatic weeds that are edible.

Certain species having potential for more widespread use are Chinese water chestnut (*Eleocharis dulcis*), water spinach (*Ipomoea aquatica*) (Figure 7.10), water lilies and taro (*Clocasia esculenta*). Duckweeds, Spirodela and Lemna , which contain high protein content (over 30% of dry weight) warrant further study. But before any waste recycling system is started, social acceptance and possible public health hazards has to be investigated.

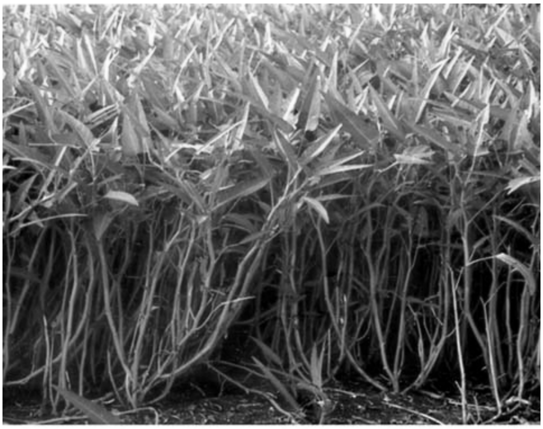

Figure 7.10 Water spinach, an aquatic plant that can be used for human consumption

7.6.3 Food for other aquatic and amphibious herbivores

The concept of harvesting aquatic weeds *in situ* can be extended to include other herbivorous animals.

Ducks, geese, and swans

Ducks, geese, swans, and other waterfowl forage on vegetation, controlling weeds on the banks of waterways and often clearing aquatic weeds and algae from small lakes, ponds and canals. In Hawaii, USA, 65 Chinese white goslings were placed in a 1 ha pond, completely covered with dense paragrass (*Brachiaria mutica*) and cattail (*Typha spp.*) that annually grew 1.8 metres above the water. Despite the failure of mechanical and chemical controls to manage the weeds for several previous years, the geese cleared them out in 2.5 years. Also, in 1967, 100 mute swans were added to Nissia Lake near Agras in northern Greece. The lake was being used to produce hydroelectricity, but the turbine inlets were clogged with aquatic vegetation. When the swans were placed in the inlet area, they cleared it within a few weeks (NAS 1976).

These waterfowl can control aquatic weeds noticeably only in small bodies of water such as farm ponds and small lakes. In a larger waterway the number of waterfowl needed to solve the weed problem makes their use impractical. Nonetheless, waterfowl could be used to supplement other weed control efforts such as the use of herbivorous fish or mechanical harvesting.

In addition to being weed-control agents, ducks and geese produce nutritious eggs and highly prized meat. Thus they provide an additional income to farmers that raise them at little extra cost. But, if not carefully managed, ducks and geese can become pests for some crops (especially grains) neighbouring their waterway. Where sanitation is poor, salmonellosis sometimes decimates ducks, geese, and swans, and this disease can be transmitted to humans. Due to the outbreaks of avian influenza (bird flu) diseases in several countries worldwide which affect the poultry and humans, the practice of using this type of animals for weed control is not attractive and should be avoided.

Turtles, rodents and manatees can be used as weed control agents, but they cannot be used for food as they are endangered species and are not usually consumed by people.

7.7 WASTEWATER TREATMENT USING AQUATIC WEEDS

Most aquatic treatment systems consist of one or more shallow ponds in which aquatic weeds are grown to enhance the treatment potential. Typically, each pond will be dominated by one species of plant, but in some cases a variety of plants will be combined for a particular treatment objective.

The presence of aquatic weeds in place of suspended algae is the major physical difference between aquatic treatment systems and waste stabilization ponds. A waste stabilization pond is highly effective if the algal population (often occurring as blooms of extremely high density) can be removed prior to final discharge of the effluent. However, algal biomass is usually carried away with the pond effluent resulting in an increase in the BOD and the production of inferior quality effluent. Thus, waste stabilization ponds which sustain good algal growth are often less effective in producing effluents having acceptable levels of suspended solids or BOD. Some of these problems associated with waste stabilization ponds can be overcome by the use of aquatic weeds. Although the latter may have slower growth rates, they can be more readily harvested, especially if they are free-floating, and therefore amenable to a simple mechanized system of continuous harvesting. Moreover, the weed growth tends to shade out the algae and prevents the erratic fluctuations in algal population densities that are a frequent characteristic of algal ponds or waste stabilization ponds.

Contrary to common opinion, the aquatic plants themselves bring about very little actual treatment of the wastewater. Their function is to provide components of the aquatic environment that improve the wastewater treatment capability and/or reliability of that environment. Reported values of oxygen transfer from leaves to the root surface of aquatic plants are 5-45 g $O_2/(cm^2$-day), with an average being 20 g $O_2/(cm^2$-day) (WEF 2001). Some specific functions of aquatic plants in aquatic treatment systems are presented in Table 7.5. These functions may be more clearly envisioned and understood by considering them in light of the morphologies of aquatic plants, some of which are shown in Figures 7.1, 7.2, 7.3 and 7.4.

Table 7.5 Functions of aquatic plants in aquatic treatment systems (Stowell *et al.* 1980)

Plant parts	Function
Roots and / or stem	Surfaces on which biofilm bacteria grow in the water column. Media for filtration and adsorption of solids
Stem and/or leaves at or above the water surface	1. Attenuate sunlight and thus can prevent the growth of suspended algae 1. Reduce the effect of wind on water 2. Reduce the transfer of gases between the atmosphere and water 3. Transfer of oxygen from leaves to the root surfaces

Aquatic treatment systems are analogous to many more common treatment systems. The principal removal mechanisms are physical sedimentation and bacterial metabolic activity, the same as is the case in conventional activated sludge and trickling filter systems. Because the plants provide a support medium for bacterial attachment and growth, aquatic treatment systems have thus been equated with a slow-rate, horizontal trickling filter.

The fundamental difference between aquatic systems and more conventional technology is the rate of treatment. In conventional systems wastewater is treated rapidly in highly managed environments whereas in aquatic systems treatment occurs at a relatively slow rate in essentially unmanaged natural environments. The consequences of this difference are:

- Conventional systems require more construction and equipment but less land than aquatic systems.
- Conventional processes are subject to greater operational control and less environmental influence than aquatic process.

Assuming land is available, the comparative economics of conventional and aquatic systems are contrasted in Table 7.6.

Table 7.6 Costs and energy requirements of conventional and aquatic treatment systems (Adapted from Stowell *et al.* 1981)

	Treatment plant size					
	$378.5 m^3$/day (0.1m.g.d)		$1892.5 m^3$/day (0.5 m.g.d)		$3785 m^3$/day (1.0 m.g.d)	
Item	Conv[a]	Aquatic[b]	Conv	Aquatic	Conv	Aquatic
Capital cost, US$ $\times 10^{-6}$	0.71	0.37	1.23	0.55	1.60	0.90
O & M cost, US$/ year $\times 10^{-3}$	35	21	78	48	117	74
Energy, kJ/year$\times 10^{-9}$	0.93	0.53	3.32	1.27	5.06	2.19

[a] Activated sludge + chlorination
[b] Primary clarification + artificial wetlands + chlorination
m.g.d = million gallons per day
O & M = operation and maintenance
kJ = kilo-joules

Aquatic treatment systems should not be confused with other types of systems that may involve the application of wastewater to wetlands for reasons other than wastewater treatment:

- Aquaculture (growth of organisms having economic value).
- Environmental enhancement (creation of habitat for wildlife).
- Wetlands effluent disposal (non point source disposal of treated wastewater).

The wetlands environment needed for each specific case can be quite varied, and therefore, a system designed to treat wastewater will be different from that designed for any other purpose.

7.7.1 Wastewater contaminant removal mechanisms

The general mechanisms involved in the removal of contaminants by aquatic weeds are discussed below.

BOD_5 removal

In aquatic systems, the BOD_5 associated with settleable solids in a wastewater is removed by sedimentation and anaerobic decay at the pond bottom. The colloidal/soluble BOD_5 remaining in solution is removed as a result of metabolic activity by micro-organisms that are:

- suspended in the water column;
- attached to the sediments, and
- attached to the roots and stems of the aquatic plants.

The microbial activity at the roots and stems is the most significant for BOD_5 removal. Reduction of colloidal/soluble BOD_5 will be, at least in part, depending on the design of the aquatic system. Direct uptake of BOD_5 by aquatic plants is not significant. Factors affecting the BOD_5 removal rate and efficiency of conventional trickling filters have similar effects on aquatic systems.

The BOD_5 of effluents from aquatic systems will be primarily the result of:

- Extra-cellular organic compounds produced by plants during the growing season, and
- Organic compounds leached from decaying vegetation during periods of vegetative die-off and dormancy.

These plant-related BOD_5 loads are part of the colloidal/soluble BOD load and should be considered as such in aquatic system design. The release of BOD_5 by plants is species specific and affected by environmental factors. The BOD_5 leakage from plants is presently not well quantified in literature, although releases upto 25% of the photosynthetically produced organic matter have been reported (Stowell *et al.* 1980).

If aquatic systems are not overloaded, effluent BOD_5 concentrations are primarily a function of the plant species grown, the growth phase of the plant, and the wastewater temperature. In such systems, effluent BOD_5 concentrations of 3-10 mg/L during the growing seasons and 5-20 mg/L during periods of dormancy can be expected. An example of the seasonality of aquatic systems effluent BOD_5 concentrations is presented in Figure 7.11. In this example, the magnitude of the winter leakage of BOD is quite high (around 30 mg/L). If the BOD_5 loading rate is either reduced in winter in conjunction with climatically induced reductions in bacterial metabolic rates and in bacterial support structure, or low on a year-round basis so as to avoid overloading the system in winter, then the effluent BOD_5 in winter would be lower than the concentrations reported in Figure 7.11.

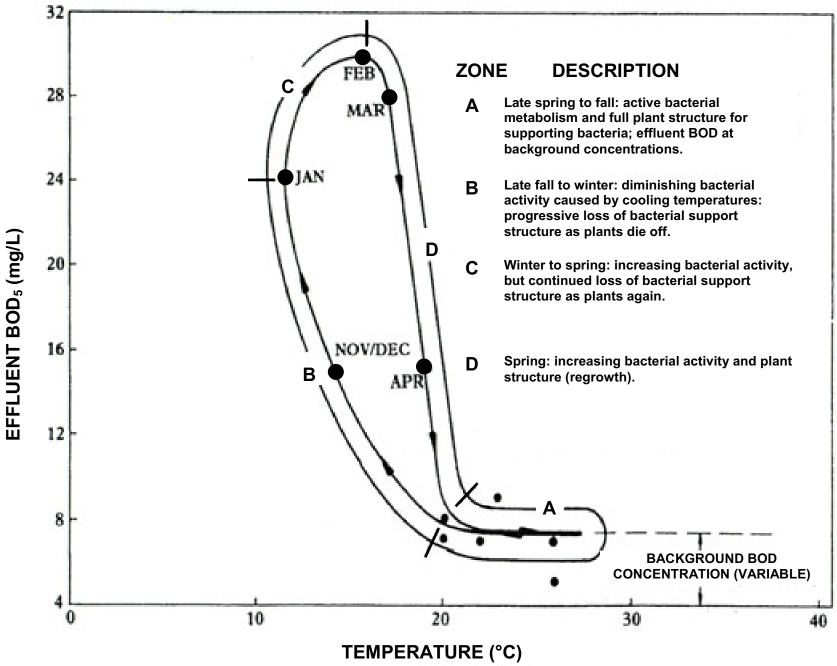

Figure 7.11 An example of the seasonality of effluent BOD_5 concentrations. *Note:* Compiled by Stowell *et al.* (1980), using data from Wolverton and McDonald (1976a). Reproduced by permission

Solids removal

Aquatic systems have long hydraulic residence times, generally several days. Consequently, virtually all settleable and floatable solids of wastewater origins are removed.

Non-settling/colloidal solids are removed, at least partially, by a number of mechanisms. Colloidal solids tend to be the foci for bacterial growth. Such growth during the residence time of the water in the aquatic system will result in the settling of some solids and the microbial decay of others. Colloidal solids will also be removed as a result of collisions (inertial and brownian) with an adsorption to other solids such as plants, pond bottom and suspended solids.

Ultimate removal of suspended solids will be by bacterial metabolism: anaerobic decay of settled solids and aerobic decay of floating solids entangled in the surfaces of vegetation. The annual build-up of stable residues from these decay processes at the bottom of aquatic systems will be quite less, so that frequent dredging of the pond bottom will not be necessary.

Solids in aquatic system effluents will be decayed or detrital to aquatic plant matter and bacterial flocs. Effluent SS concentrations are a function of water velocity and turbulence in the aquatic system, the type(s) of plant being grown, and the time of the year. An important function of the plants in aquatic systems is attentuation of sufficient light to prevent algae growth. The plants also help reduce the effects of wind (e.g., water turbulence) on aquatic systems. Effluent SS concentrations are normally less than 20 mg/L, typically, and often less than 10 mg/L, particularly during summer and fall.

Nitrogen removal

Nitrogen is removed from wastewater by a number of mechanisms:

- Uptake by plants and subsequent harvesting of them.
- Volatilization of ammonia.
- Bacterial nitrification/denitrification.

Of these, bacterial nitrification/denitrification has the greatest nitrogen removal potential. To maintain significant populations of the slowly reproducing nitrifying bacteria in an aquatic system, the aquatic plants provide structure to which these organisms can attach. For bacterial nitrification to occur, the DO concentration of the wastewater must be above 0.6-1.0 mg/L (Metcalf and Eddy Inc. 2003). Thus, the depth of zone below the water surface in which nitrification will occur is a function of BOD loading rate and oxygen flux into the aquatic environment. In estimating the depth of this zone for the purpose of providing sufficient support structure for the design nitrification rate, the oxygen used in nitrification must be added to that used to metabolize soluble/colloidal BOD. The rate of nitrification also depends on water temperature, and is very slow at temperatures below 10 °C.

Denitrification is an anoxic metabolic pathway used by specific bacterial genera in aquatic environments characterized as having little or no dissolved oxygen, an adequate supply of carbon for cell synthesis and neutral pH. These criteria are met readily in the bottom sediments and detrital layer of aquatic systems thus leading to rapid denitrification. The rate of denitrification depends on:

- the metabolic activity of the bacteria, i.e., environmental factors such as organic carbon availability, pH, and wastewater temperature;
- the effective surface area of the bottom sediments, and
- the potential for the produced N_2 to escape to the atmosphere rather than be fixed in the overlying water of vegetation.

Nitrogen uptake by plants and its subsequent removal by harvesting plants is another mechanism of nitrogen removal. The N-uptake is quite high in plants grown in primary sewage effluent, but is very low for plants cultured in secondary sewage effluent. This is due to the following reasons:

- Low concentration of the inorganic N in the influent.
- Plant-available N in the secondary sewage effluent is present in NO_3^- (nitrate) form compared with NH_4^+ in the primary sewage effluent. A significant portion of NO_3^- in the secondary sewage effluent is lost through denitrification (Reddy and Sutton 1984).

Thus, harvesting plants, especially those grown in secondary sewage effluents, remove little nitrogen directly. However, the indirect effects of plant harvesting on oxygen transfer rates and the quantity of bacterial support structure in the aerobic zone may affect the rates of bacterial nitrification and denitrification significantly.

Phosphorus removal

Phosphorus removal mechanisms in aquatic systems are plant uptake and several chemical adsorption and precipitation reactions (occurring primarily at the sediment/water column interface).

In general, chemical adsorption and precipitation are more significant mechanisms of removal (Whigham *et al.* 1980) because:

- the potential rates of phosphorus removal by these mechanisms are greater than that achievable by plant uptake, and
- harvesting and disposal of plants is not a necessary part of removing phosphorus by chemical means.

However, the removal of phosphorus by chemical reactions cannot be predicted accurately because of the many competing and interacting reactions occurring simultaneously in the water column, detrital layer and sediments. The major factors determining how much and at what rate phosphorus will be stored in an aquatic system as a result of chemical reactions are pH, redox potential, and the concentrations of iron, aluminium, calcium, and clay minerals. For example, at pH greater than 8, metal phosphates precipitate from solution. While, at pH less than 6 and redox potential greater than 200 mv, phosphate adsorbs strongly to ferric oxyhydroxides and similar compounds. Many other phosphate retaining reactions occur to a greater or lesser extent depending on the aquatic environment. General conclusions as to what aquatic environmental conditions will maximize phosphorus removal have not been reached, and phosphorus removals from various aquatic treatment research projects and systems have not been consistent (Cornwell *et al.* 1977; Dinges 1979; Reddy and Sutton 1984; Wolverton and McDonald 1976a).

Ultimate disposal of phosphorus from aquatic system is by:

- harvesting the plants;
- dredging the sediments, and
- desorbing/ re-solubilizing phosphorus stored in the sediments and releasing it to the receiving water when it will have the least environmental impact.

Selection of the method will depend on design considerations such as the discharge permit, environmental factors, and the rate of sediment build-up as compared to the rate of phosphorus accumulation.

Heavy metals removal

Heavy metals are removed from wastewater during aquatic treatment by:

- Plant uptakes;
- Precipitation as oxides, hydroxides, carbonates, phosphates, and sulfides, and
- Ion exchange with and adsorption to sedimented clay and organic compounds.

Although plants can concentrate some metals by over three orders of magnitude above the concentration in water (O'Keefe *et al.* 1984; Wolverton and McDonald 1976b), the potential of this removal mechanism is small compared to that of the other removal mechanisms.

The principal means for removing heavy metals during aquatic treatment is by controlling the aquatic environment to optimize the precipitation and ion exchange/adsorption removal mechanisms. The rate of removal and storage capacity associated with these mechanisms are functions of redox potential, pH, the presence of clay minerals and insoluble/particulate organic matter, and the concentrations of co-precipitating elements and related compounds, such as sulfur, phosphorus, iron, aluminium, manganese and carbonate. Unfortunately, wetlands environments are sufficiently complex to preclude accurate theoretical determination of what environmental conditions will result in maximum removal of heavy metals in a given situation. The results of field observations and experiments in this area have not been conclusive.

To some extent heavy metals will be removed in every aquatic system. The extent of removal is affected by aquatic system design and management as well as wastewater quality (including pretreatment). Resolubilization of sediment-stored heavy metals (intentionally for discharge or accidentally as a result of process upset) can occur. Ultimate disposal of heavy metals from aquatic systems will be by the methods discussed for phosphorus in the previous section.

Refractory organic removal

In aquatic systems refractory organic compounds are removed from solution by adsorption to intrasystem surfaces and are altered chemically by physical, chemical, and biological decay processes. During the residence time of a wastewater in an aquatic system, chemically unstable compounds will disintegrate and the diverse bacterial populations, characteristic of aquatic systems, will metabolize the more biologically degradable compounds. Refractory organics more resistant to chemical and/or biological decay will be removed, at least partially, by adsorption to the bottom sediments, detrital layer, or "ooze" layer enveloping the submerged parts of plants (once adsorbed, decay as a result of bacterial or botanical metabolism and/or physical/chemical processes takes place).

Aquatic systems are reported to remove phenolic compounds, chlorinated hydrocarbons, petroleum compounds, and other refractory organics (Dinges 1979; Seidal 1976). Quantification of the removal of specific refractory organic compounds from a specific wastewater by means of aquatic treatment methods will require detailed studies (Stowell *et al.* 1980).

Removal of bacteria and viruses

In aquatic systems concentrations of pathogenic organisms are reduced by prolonged exposure (days) to physical, chemical, and biological factors hostile to these organisms. Physical factors include sedimentation and exposure to ultra violet (UV) radiation. Chemical factors include oxidation, reduction, and exposure to toxic chemicals, some of which may be excreted by plants (Seidal 1976). Biological factors include attack by other organisms (particularly bacteria) and natural die-off as a result of being away from a suitable host organism for a long period of time.

However, the extent and reliability of reductions in pathogen concentrations in aquatic systems is unknown. In most wastewater treatment situations some form of disinfection e.g. chlorination, is necessary to satisfy public health and water quality requirements.

Summary

The principal wastewater contaminant removal mechanisms operative in aquatic treatment systems are summarized in Table 7.7. The effect of each mechanism depends on the design and management of the aquatic system, the quality of the influent wastewater, and climatic and environmental factors.

7.7.2 Aquatic system design concepts

Design concepts for aquatic treatment systems differ somewhat from those for conventional systems because aquatic systems have larger surface areas, longer hydraulic detention times, and aquatic plants. The aquatic environment or series of environments necessary to achieve the desired level of wastewater treatment must be envisioned. The plants, and equipment, to maintain this environment must be selected. The effects of climatic and environmental factors on the aquatic treatment processes must be anticipated and mitigating measures taken as necessary. These concepts and others are part of the rational design of an aquatic treatment system.

Aquatic processing unit (APU)

An APU is an assemblage of plants (and possibly animals) grouped together to achieve specific wastewater treatment objectives. One or more APU's constitute an aquatic system. In this regard APU's are similar to conventional processes making up a conventional system but direct comparisons between APU's and specific types of conventional processes cannot be made in general. However, this does not preclude the use of APU's in conjunction with conventional processes. The conceptual use of APU's to accomplish various treatment objectives is illustrated in Figure 7.12.

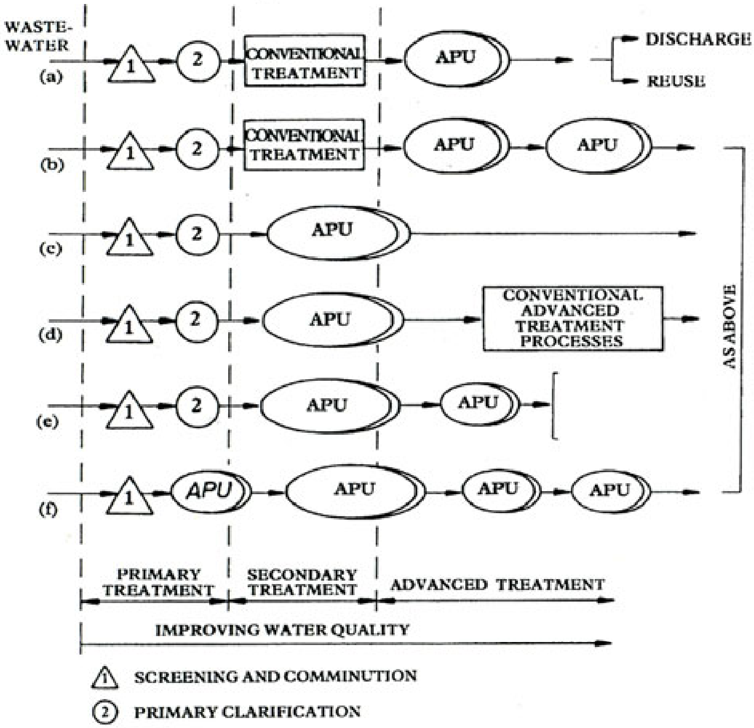

Figure 7.12 Conceptual uses of APUs (aquatic processing units) for the treatment of wastewater (Tchobanoglous *et al.* 1979)

The APU's in Figure 7.12 are arranged so that the application is from least to most complex conceptually. In levels (a) and (b) of Figure 7.12, the APU's are used for the removal of nutrients, refractory organics, and/or heavy metals. In contrast to this relatively simple application, the complete treatment of wastewater is envisioned in level (f).

Table 7.7 Contaminant removal mechanisms in aquatic systems

Mechanism	Contaminant affected[a]								description
	Settleable solids	Colloidal solids	BOD	Nitrogen	Phosphorus	Heavy metals	Refractory organics	Bacteria and viruses	
Physical									
Sedimentation	P	S	I	I	I	I	I	I	Gravitational settling of solids (and constituent contaminants) in ponds/marsh settings.
Filtration	S	S							Particulates filtered mechnically as water passes through substrate, route masses, or fish.
Adsorption		S							Inter particle attractive force (Van der Waals force)
Chemical									
Precipitation					P	P			Formation of, or co-precipitation with, insoluble compounds.
Adsorption					P	P	S		Adsorption on substrate and plant surfaces.
Biological									
Bacterial metabolism[b]		P	P	P			P		Removal of colloidal solids and soluble organics by suspended, benthic, and plants- supported bacteria: bacterial nitrification/denitrification.

Table 7.7 Contaminant removal mechanisms in aquatic systems (continued)

Mechanism	Contaminant affected[a]								description
	Settleable solids	Colloidal solids	BOD	Nitrogen	Phosphorus	Heavy metals	Refractory organics	Bacteria and viruses	
Plant metabolism[b]							S	S	Uptake and metabolism of organics by plants; root excretion may be toxic to organisms of enteric origin.
Plant adsorption				S	S	S	S		Under proper conditions significant quantities of these contaminants will be taken up by plants.
Natural die off								P	Natural decay of organisms in an unfavourable environment.

[a] P = primary effect, S = secondary effect, I = incidental effect (effect occurring incidental to removal of another contaminant)
[b] The term metabolism includes both biosynthesis and catabolic reactions
From Tchobanoglous *et al.* 1979; reproduced by permission

Use of plants and animals in aquatic treatment

The fundamental purpose of plants, animals and the management of these organisms in aquatic systems is to provide components to the aquatic environments that improve the rate and/or reliability of one or more of the contaminant removal mechanisms to be operative by design in the aquatic treatment system. Plants play a more dominant role than animals in aquatic systems because plants have a greater effect on the aquatic environment and are more adaptable to harsh and/or fluctuating environment.

Aquatic animals are used, primarily, as biological controls of insect vectors and as bioassay organisms for monitoring the treatment performance of an APU or aquatic system. In certain situations animals can also play a role in plant harvesting and suspended solids removal. In general, however, the direct uptake and/or removal of wastewater contaminants by plants and animals are not significant treatment mechanisms. An observation of interest is that some molecular oxygen produced by the photosynthetic tissue of plants is translocated to the roots and may keep root zone microorganisms metabolizing aerobically, though the surrounding water is anoxic (Tchobanoglous *et al.* 1979).

7.7.3 Process design parameters

The different parameters currently being used in the design of aquatic systems include organic loading rate, hydraulic loading rate, hydraulic application rate, hydraulic detention time, and nitrogen loading rate. Depending on the treatment objective the major design parameter will be different, for example, organic loading rate is important for organic matter removal. Root depth of the plant is important as it provides the bacterial support and the media for interaction between wastewater and the bacterial mass. Even though there are many potential aquatic plants that can be used for waste treatment they have not yet been investigated to develop rational design criteria. Design criteria for water hyacinth treatment systems are given below, while some data from the existing systems are given in section 7.7.4.

Hydraulic retention time and process kinetics

Hydraulic retention time, typically expressed in days, is the most frequent parameter used to design aquatic systems. The greatest benefit derived from the use of hydraulic retention time is that a majority of performance data reported in the literature are correlated to retention time. The use of hydraulic retention time, however, has some serious drawbacks. Depending on system geometry, systems with similar hydraulic retention times may be quite different hydraulically. Also, accurate determination of hydraulic retention time is difficult in aquatic treatment systems because of complex flow patterns and volume displacement attributable to the plants. Generally, hydraulic retention times reported in the literature are based on the assumption of their ideal complete mix or plug flow hydraulics, neither of which are valid assumptions. In addition, no attempt has been made to account for plant volume displacement in the hydraulic retention times reported in the literature. Very little data are available for hydraulic characterization of existing aquatic systems. In summary, while hydraulic retention time has been used widely as an aquatic system design parameter, little insight into how the hydraulic conditions affect the efficiency of pollutant removal mechanisms can be derived from its usage.

Based on performance data of water hyacinth ponds used to treat domestic wastewaters on San Diego, California, U.S.A. and elsewhere, it was suggested that if the length/width ratios of the ponds are not great (probably less than 3/1), a first order complete mix reaction may be applied (WEF 2001) as shown in Equation 7.4.

$$\frac{C_e}{C_0} = \frac{1}{1 + k_t t} \tag{7.4}$$

Where:

C_0 = Influent BOD_5 concentration, mg/L

C_e = Effluent BOD_5 concentration, mg/L

k_t = first order BOD_5 removal rate constant at temperature $T\,^{\circ}$C, day^{-1}

T = Liquid temperature, ^{0}C

k_{20} = first order BOD_5 removal rate constant at 20° C, day^{-1}

k_T = $k_{20}(1.06)^{T-20}$

t = hydraulic retention time, days

The estimated k_{20} value is 1.95 day^{-1}

To describe the process kinetics of water hyacinth ponds in more details, Polprasert and Khatiwada (1998) developed an integrated kinetic model which encompasses the effects of both the suspended and biofilm bacteria and the hydraulic dispersion number on the BOD_5 removal efficiency. Based on a dispersed flow model, an equation to predict BOD_5 removal efficiency is shown in Equation 7.5.

$$\frac{C_e}{C_0} = \frac{2a_1 e^{1/2d}}{(1 + a_1)e^{-a_1/2d} - (1 - a_1)e^{-a_1/2d}} \tag{7.5}$$

Where:

C_e, C_o, and t = as defined in Equation (7.4)

$a_1 = \sqrt{1+4k.t.d}$ (7.6)

d = dispersion number, which is 0 at plug flow and infinite at complete mix condition

$k = k_{fs} + k_{fb} .a_s$ (7.7)

k_{fs} = first-order rate constant for suspended bacteria, day^{-1}

k_{fb} = first-order rate constant for biofilm bacteria, day^{-1}

a_s = specific surface area of water hyacinth ponds, m^2/m^3

$a_s = 1/z + 2/w + 2/l + R_s/z$ (7.8)

z = pond depth, m

w = pond width, m

l = pond length, m

R_s = effective root surface area per unit pond area of surface area, m^2/m^3

For a pond with relatively large width and depth,

$a_s = (1+R_s)/z$ (7.9)

To use Equation (7.5) is predicting BOD_5 removal efficiency; the values of the above parameters have to be determined experimentally or obtained from the literature. Figure 7.13 determines the applicability of Equation (7.5) in predicting the effluent BOD_5 concentration of a water hyacinth pond treating a domestic wastewater and showing the significance of the biofilm bacteria attached on the root surfaces in BOD_5 removal. To assist in the calculation, a diagram based on Equation (7.5) and showing the relationship among BOD_5 removal efficiency, $k.t$ and d is given in Figure 7.14. Example 7.1 demonstrates the application of Figure 7.14 in the design of a water hyacinth pond for wastewater treatment.

Example 7.1

A water hyacinth pond is designed to treat a wastewater whose flow rate is 500 m^3/day and BOD_5 concentration is 200 g/m^3. Determine the appropriate dimensions of this pond so that at least 90% BOD_5 removal is achieved. The following information is given; $d = 0.2$, $T = 20^oC$, $z = 1.5$ m, $R_s = 1.18$ m^2/m^3, $k_{fs} = 0.07$ day^{-1}, $k_{fb} = 0.048$ day^{-1}.

From Equation 7.9,

$$a_s = (1+1.18)/1.5 = 1.45\ m^2/m^3$$

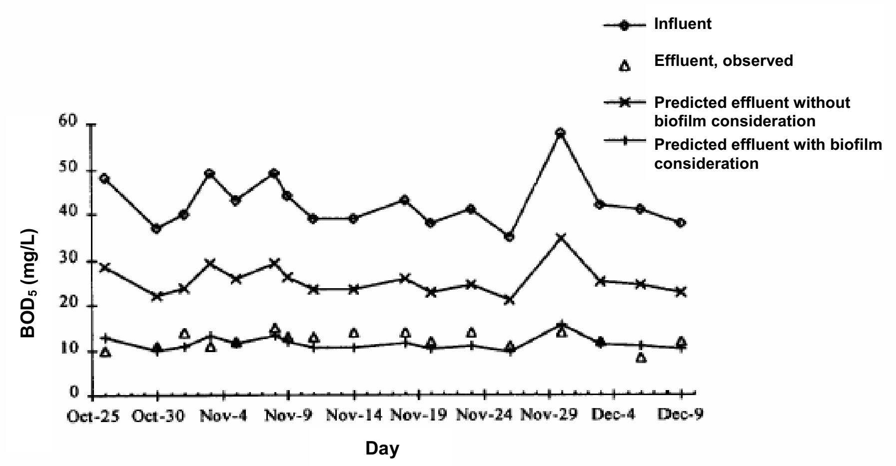

Figure 7.13 Predicted and observed effluent BOD_5 concentration of the WHP (Polprasert and Khatiwada 1998)

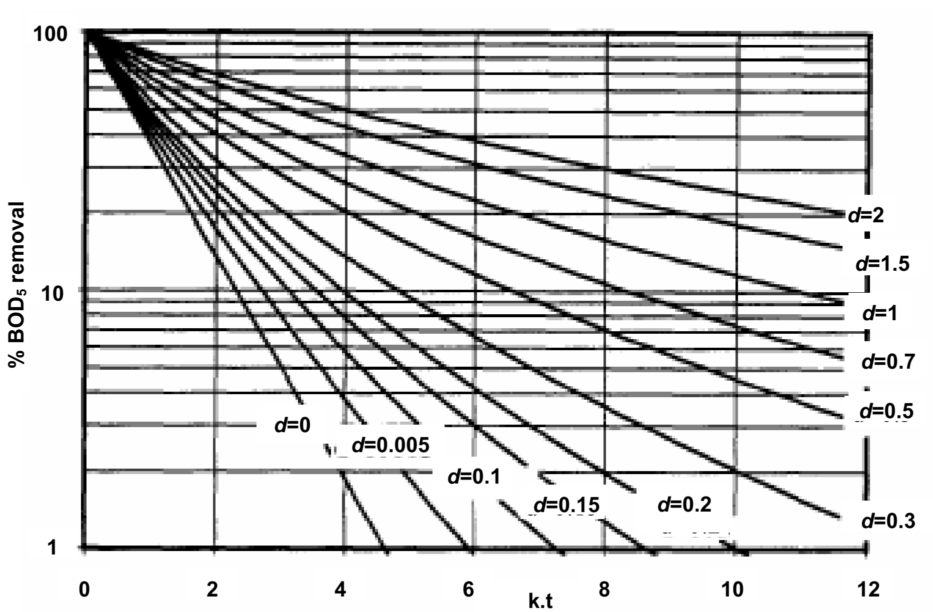

Figure 7.14 Design chart for BOD_5 removal in water hyacinth ponds (Polprasert *et al.* 1998)

From Equation 7.7,

$k = 0.07 + 1.45\ (0.048) = 0.14\ day^{-1}$

From Figure 7.15, for the 10% BOD_5 remaining and d = 0.2, the value of $k.t$ is 4.

Therefore the value of t is 4/0.14 or 28.6 days.

Chose a "t" value of 30 days, the pond area is 500 × 30/1.5 = 10,000 m^2. The dimension of this water hyacinth pond is 200 × 50 × 1.5 m^3 (length × width × depth). *Note*: a freeboard of about 0.5 m should be added to the depth of this pond.

Check for BOD_5 loading rate = 500 m^3/d × 200 g/m^3 × 1/10,000 m^2
= 100 kg/(ha-day)

Note: the value of organic loading rate determined from this example is within the range shown in Figure 7.15 and should result in about 90% BOD_5 removal. If, due to evapotranspiration, the effluent flow rate value is much less than 500 m^3/day, average between the influent and effluent flow rate should be used in calculating the pond dimensions.

Hydraulic loading rate

Hydraulic loading rate, expressed in units of m^3 / (m^2-day), is the volume of wastewater applied per day per unit surface area of the aquatic system. Most likely, the use of hydraulic loading rate stems from its popular use in land application systems. Typically, aquatic systems are operated in a continuous flow manner and as a result hydraulic loading or dosing rate is not a pertinent design parameter.

Hydraulic application rate

Hydraulic application rate refers to the volumetric flow rate of wastewater applied to the aquatic system per unit cross sectional area of the reactor assuming the wastewater is applied uniformly to the system. The unit for this parameter is m^3 / (m^2-day), which reduces to an expression of fluid velocity. Hydraulic application rate has not been used widely, but offers a much better unit of comparison for system performance data than the aforementioned parameters for several reasons. One reason hydraulic application rate should be a better design parameter is because hydraulic application rate is a gauge of the fluid velocity that is thought to have a significant effect on removal mechanisms operative in aquatic systems. In addition, hydraulic application rate can be compared directly from system to system.

Organic loading rate

Organic loading rate, expressed as kg / (m^2-day), is the mass of applied organic material per unit surface area of the system per unit time. It is a function of flow rate and concentration of organic matter. Theoretically, organic loading rates are dictated by a balance between the applied carbon and available oxygen based on the oxygen/carbon stoichiometry of bacterial conversion. In practice, organic loading rates, based on experience, are dependent on effective distribution of wastewater to the system. To avoid odour problems due to uneven organic loading, the wastewater should be distributed evenly over the entire pond system.

A relationship between average BOD_5 loading and removal rates for aquatic systems obtained from 24 different studies is shown in Figure 7.15. These data suggest that aquatic systems using either emergent or floating plants could be designed at BOD_5 loading rates up to approximately 110 kg / (ha-day) with 80% or more of the applied BOD_5 being removed. It is apparent that a low effluent BOD_5 concentration from aquatic systems can be achieved with a reduced BOD_5 loading rate. BOD_5 removal rates naturally decrease during the winter period if the influent wastewater has a low temperature (Figure 7.11).

Nitrogen loading rate

Nitrogen loading rate, expressed as kg / (m^2-day), is defined as the mass of applied nitrogen to the system per unit surface area per unit time. If plants are being harvested on a regular basis, the nitrogen requirement for new plant reproduction can be matched with the system nitrogen loading rate. Early in the development of aquatic systems, nitrogen removal by plant uptake and subsequent harvesting was suggested as the principal removal mechanism. More recently the potential for nitrogen removal through nitrification/denitrification has been identified. If nitrification is the major step for total nitrogen removal, then nitrogen loading rate is not a valid design parameter. System environmental conditions favoring nitrification are different from those that would enhance denitrification. As a result, a loading rate based on a lumping of the various forms of influent nitrogen into a single unit is not fundamentally sound.

From their experimental study Weber and Tchobanoglous (1985) found ammonium nitrogen removal rate in an aquatic (water hyacinth) system to be a function of the hydraulic application rate and reactor length. The ammonium nitrogen conversion rate was independent of the ammonium loading rate; and hydraulic retention time was not recommended as a design parameter. As shown in Figure 7.16, ammonium removal rates were observed to be inversely proportional to the hydraulic application rates, while Figure 7.17 shows the concentrations of ammonium nitrogen removal to be proportional to the reactor length within the experimental conditions employed.

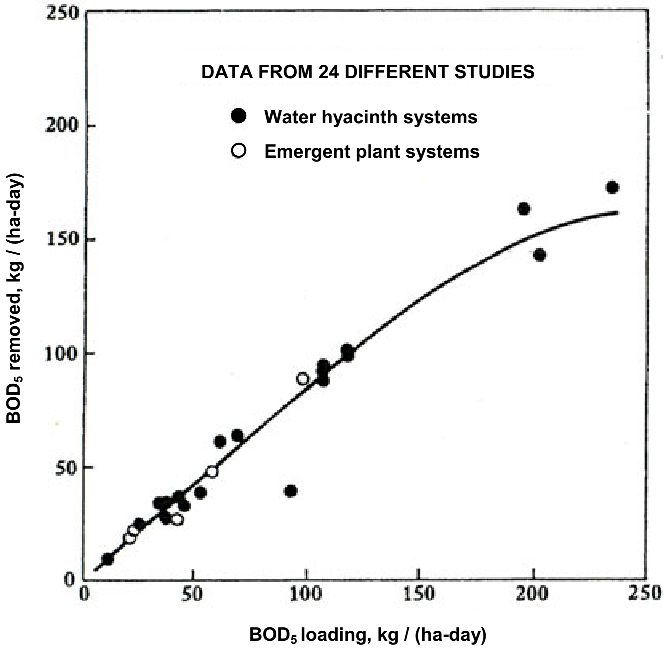

Figure 7.15 BOD removals as a function of BOD loading in aquatic systems (after Stowell *et al.* 1981; reproduced by permission of the American Society of Civil engineers)

Weber and Tchobanoglous (1986) developed an equation for ammonium nitrogen removal in water hyacinth reactors as follows:

$$N_r = \frac{k.l}{q} \tag{7.10}$$

Where,
N_r = ammonium nitrogen removal, mg/L
k = rate coefficient, mg/(L-day)
q = hydraulic application rate, m^3/m^2-day
l = reactor distance, m

Based on the data shown in Figure 7.17, the values of k as a function of q are given in Table 7.8.

Climatic influences

Surface area loading rates are much lower in aquatic systems than conventional systems, typically more than two orders of magnitude lower. A consequence of these lower loading rates is greater exposure to climatic factors such as temperature, rain, and wind. Any of these factors can disrupt treatment by altering the aquatic environment or damaging the plants. In general, the use of aquatic plants native to the climatic regime at the aquatic system site is encouraged but, in certain cases, this may not be desirable or possible.

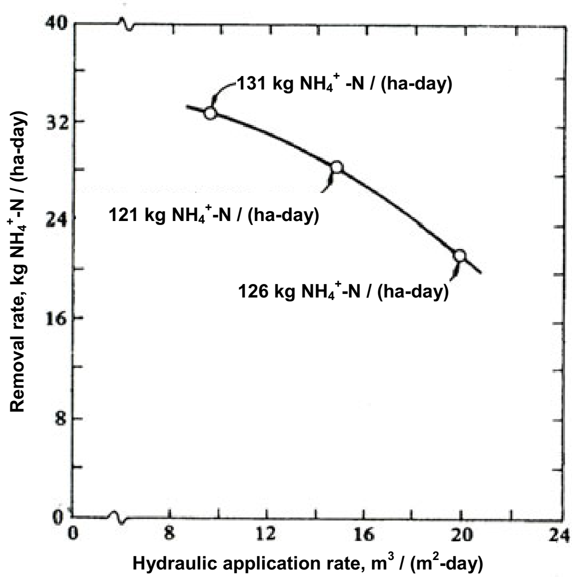

Figure 7.16 NH_4^+- N removal as a function of hydraulic application rate (corresponding loading rates for NH_4^+- N are as shown) (after Weber and Tchobanoglous 1985; reproduced by permission of the Water Pollution Control Federation, USA)

Temperature

Wastewater in aquatic systems will be warm in summer and cool in winter because of the large surface areas and long hydraulic residence times. A 10°C rise or drop in temperature is generally known to double or halve the metabolic rate of bacteria and plants. Temperature has a similar effect on the reproductive rates of these organisms.

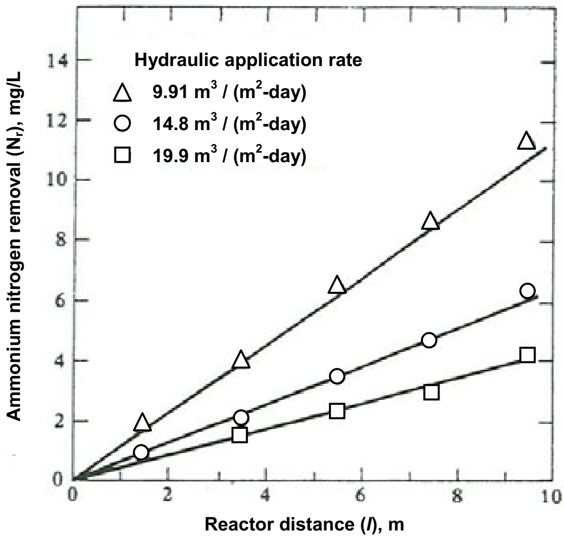

Figure 7.17 Ammonium nitrogen removal (N_r) as a function of reactor distance for three hydraulic application rates (after Weber and Tchobanglous 1986; reproduced by the permission of the Water Pollution Control Federation, USA)

Summer high temperatures may upset treatment by causing damage to some plant species and/or by increasing bacterial metabolic activity, resulting in altered balances between BOD_5 reduction rates and oxygen flux from the atmosphere. Another potential problem is that the water may become sufficiently warm to result in violations of discharge permit requirements on water temperature or other factors affected by water temperature such as un-ionized ammonia concentration.

Winter low temperatures will reduce the metabolic rate of bacteria and may kill many plant species. A plant kill may, but not necessarily, result in loss of bacterial structure and/or leakage of plant-contained compounds. Research in this area is necessary. As water temperatures approaching 0°C metabolic activity virtually ceases, thus, wastewater treatment would result only from physical/chemical mechanisms. This reduced level of treatment may be inadequate in some situations. In these cases aquatic treatment would have to be considered a seasonal treatment process. Wastewater storage or some other form of treatment would be necessary during the periods when the aquatic system is not functional.

Rain

Rain storms could overload aquatic systems hydraulically. Water inflow will increase from I/I (inflow/infiltration) and direct rainfall into the APU's. Direct rainfall alone from a typical storm could more than double the hydraulic load to an aquatic system. The nature, magnitude, and duration of effects resulting from hydraulic overloading are unknown. Probable effects of hydraulic overloading would include wash-through of BOD_5, re-suspension of sediment, and addition of dissolved oxygen to APU's designed to be anaerobic.

Table 7.8 Calculated value of the rate coefficient, *k* as a function of hydraulic application rate (Weber and Tchobanoglous 1986)

Hydraulic application rates (m^3/m^2-day)	*k* (mg/L-day)
9.91	11.9
14.8	9.47
19.9	8.77

Note: k =hydraulic application rate multiplied by the slopes from Figure 7.17

Wind

Wind can alter the aquatic environment directly or indirectly, the latter by damaging the plants. Wind increases the rate of gas transfer between the wastewater and atmosphere. Wind also increases water turbulence, which may result in re-suspension of sediment. Plants broken or otherwise damaged by wind may not function as intended, which would upset the wastewater treatment process until the plants have recovered. Floating plants, particularly duckweeds, are more sensitive to wind than rooted plants because the former tend to be blown around and may result in open water surfaces which are vulnerable to the direct effects of wind and other environmental factors. Though more sensitive to winds, floating plants, by virtue of their mobility, are less likely to be physically damaged by wind than rooted plants.

Environmental factors

Environmental impacts that could result from the presence of an aquatic treatment system include odors, fog generation, increased vector-organism population, and introduction of nuisance organisms to the local environment. The potential for significant environmental impact from any of these or other factors must be evaluated and mitigating measures taken as necessary.

The potential of the local environment to have significant impact on the organisms in the aquatic system must also be evaluated. Of particular concern in this regard are:

- local and/or migratory animals that may eat the APU plants, damage APU levees by burrowing, or upset APU hydraulics by either channelizing or blocking flow, and
- local plant diseases or plant-consuming insects.

As an example, water hyacinths could not be used for wastewater treatment in an area where biological control of water hyacinths has been established.

Wastewater characteristics

Contaminant concentrations in domestic wastewaters should not be toxic to aquatic plants in properly designed APU's. As the industrial fraction of the wastewater increases, the chance of contaminants occurring in toxic concentrations on a regular basis, or as shock loadings, increases. When an appreciable portion of the wastewater is of industrial origins, small-scale pilot studies should be conducted to evaluate the toxicity of the wastewater. If toxicity from shock loadings occurs, mitigating measures such as flow equalization/storage facilities will be necessary. If the wastewater is consistently toxic, source control, pretreatment, or processes other than aquatic treatment will be necessary.

Process reliability, upsets, and recovery

Little is known about the reliability of aquatic systems. The greater influence of climatic and other environmental factors on aquatic processes should reduce their reliability in comparison to conventional processes. However, the slower rate of treatment, reduced reliance on equipment, and greater bacterial diversity of aquatic processes should improve their reliability, comparatively. Currently operating aquatic processes have not been as reliable as conventional processes; but considering how little is known about the design, monitoring, and management of aquatic processes, significant improvement in reliability should be achievable.

Causes of aquatic process upsets and the nature, magnitude, and duration of disruption of treatment have not been studied. Once rational aquatic treatment design criteria have been established, most process upsets will result from:

- unusual climatic and environmental events insufficiently accounted for in design, and
- improper APU management, such as lack of plant harvesting, etc.

The nature, magnitude, and duration of treatment process disruption will depend, primarily, on the severity of the event causing the upset, which APU's are affected, and the extent of damage/alteration to the aquatic environment.

Essentially nothing is known about the recovery times of aquatic processes from various types and magnitudes of upsets. Recovery times are expected to be longer in aquatic processes than conventional processes because environmental conditions in the former are less conducive to rapid bacterial growth rates. If a necessary function of the APU plants is damaged, the recovery time could be several weeks or more if a new group of plants must be grown.

7.7.5 Review of existing aquatic treatment systems

There is a vast amount of literature available on aquatic treatment systems. O'Brien (1981) summarized the design and performance characteristics of such systems in the U.S., as shown in Tables 7.9 and 7.10. Most of these systems are in the hotter parts of the U.S. and the climate there closely resembles the tropical climates of developing countries. The wide differences in design parameters shown in Table 7.9 are typical for an emerging technology. But sufficient information is now available to suggest the criteria shown in Table 7.9 for the design of water hyacinth systems intended to produce secondary or advanced secondary effluents. Criteria similar to those given in Table 7.9 were also recommended by Dinges (1979), who focused on the development of low technology systems suitable for upgrading lagoon performance in small towns. Suggestions by Dinges (1979) to supplement the design criteria in Table 7.9 include the use of:

- Perforated pipe to achieve uniform influent flow distribution;
- Filters around the effluent structure to prevent the escape of plants, and
- Circular galvanized wire-mesh enclosures in ponds to improve production of the fish used for controlling mosquitoes.

The data in Table 7.10 suggests that secondary waste treatment standards can be met if intensive management techniques are practiced. Ultimate disposal of the harvested plants as surface mulch, compost, animal feed, or for generation of biogas (see sections 7.5 and 7.6) ensures that resource recovery is also practiced. But, in most wastewater treatment installations, these processes will not be sufficiently profitable to offset the cost of solids disposal (because performances of natural treatment systems are site specific and dependent on climatic and related factors, wherever possible, pilot-scale experiments should be done to confirm the selected design criteria).

Table 7.9 Summary of design and performance characteristics of aquatic weed wastewater treatment systems

Location	Types of pre-treatment	Surface area of hyacinth ponds (ha)	Depth of hyacinth ponds (m)	Hydraulic loading rate, (m^3/ha-day)	Hydraulic residence time (days)	Organic loading rate (kg/ha-day)	Hyacinth cover (%)	Nutrient content of plants, dry weight, (%)	
								Total Kjedahl nitrogen	Total phosphorus
National Space Technology Lab:	None	2	1.22	240	54	26	100	2.73	0.45
Lucedale, Miss	None	3.6	1.73	260[a]	~ 67[a]	44	100	3.56	0.89
Orange Grove, Miss.	Facultative lagoons	0.28	1.83	3,570	6.8	179	100	3.75	0.85
Ceder Lake, Miss (Duckweed)	One aerated and one facultative lagoon	0.07	1.5	700	22	31	100	-	-
Williamson Creek, Tex.:									
Phase I	Plant A: aeration basin, clarifier, three lagoons in series	0.06	1.0	1,860	5.3	43	100	-	-

Table 7.9 Summary of design and performance characteristics of aquatic weed wastewater treatment systems (continued)

								Nutrient content of plants, dry weight, (%)	
Location	Types of pre-treatment	Surface area of hyacinth ponds (ha)	Depth of hyacinth ponds (m)	Hydraulic loading rate, (m^3/ha-day)	Hydraulic residence time (days)	Organic loading rate (kg/ha-day)	Hyacinth cover (%)	Total Kjedahl nitrogen	Total phosphorus
Austin- Hornsby Bend, Tex.:	Excess activated sludge lagoons overflow to hyacinth ponds	1.4	1.23	430	~3		100		
University of Florida, Gainseville,Fla	Trickling filter and activated sludge with polishing pond	0.76	1.4	1220	0.63	5.2	100		

[a] Based on effluent flow rate

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Table 7.10 Summary of influent/effluent characteristics of aquatic weed wastewater treatment systems

Location	BOD_5 (mg/L)		Suspended solid(mg/L)		TN (mg/L)		TP (mg/L)		Dissolved oxygen, (mg/L)	Effluent pH values	Sampling period and comments
	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.			
National Space Technology Lab:											
Before hyacinths	91	17	70	49	9.8	5.2	2.9	2.1	6.9	9.3	May 1974-May1976
After hyacinths	110	7	97	10	12.0	3.4	3.7	1.6	2.3	7.1	June 1976-September 1977
Lucedale, Miss.:											
Before hyacinths	127	57	140	77					0		Odors at night
After hyacinths	161	23	125	6							
Orange Grove, Miss.:											
Without hyacinths	50	37	49	53					2.0		
With hyacinths	50	14	49	15							
Cedar Lake, Miss. (duckweed)	44	18	188	11					0.5		
Williamson Creek, Tex.:											
Full-scale	42	12	40	9							

[a] Only partial cover and limited preliminary data
[b] Experimental units not fully operational
From O'Brien (1981); reproduced by permission of the American Society of Civil Engineers

Example 7.2

Design a water hyacinth treatment system to treat the following wastewater.

Wastewater characteristics:

BOD_5 = 200 mg/L
COD = 300 mg/L
Flow Rate = 100 m^3/day

Choose organic loading = 25 kg BOD/ (ha-day) (From Table 7.9)
Area required = 100 x 200 x 10^{-3}/ (25)
= 0.8 ha
If two basins are to be constructed,
Area of individual basin = 0.4 ha
Length: width = 4: 1
Width = $(0.4 \times 10^4/4)^{0.5}$ = 31.6 m
Choose width = 32 m
Length = 125 m
Choose depth = 1.2 m (Root depth = 0.9 m; bottom layer = 0.3 m
Check with data in Table 7.9
Hydraulic loading rate = 100/(2 x 0.4)
= 125 m^3/(ha-day)
Hydraulic retention time = 4000 x 1.2 x 2 / (100)
= 96 days
The design is acceptable.

Example 7.3

Estimate the yield of duckweeds from an aquatic treatment system treating domestic sewage.

Area of ponds = 1 ha (or 10^4 m^2)
Doubling time of duckweed = 10 days
Choose stocking density = 400 g/m^2 (wet weight)
Note:

- Stocking density reported in the literature varies from 200 g/m^2 to 700 g/m^2
- Lower initial density may cause algal blooms that could suppress the growth of duckweed.
- Harvesting interval has to be chosen such that the growth of duckweed is not reduced due to overcrowding.

To compensate for other factors, choose the harvesting interval to be once every 10 days, and to maintain continuous duckweed growth, only 50 % of the total duckweeds or 50 % of the pond area are to be harvested.

Amount of duckweeds to be harvested each time = $(400 \times 10^4$ g$)/2$
= 2 tons

Monthly harvest = 2 x 30 /(20)
= 6 tons wet mass

If duckweeds contain 95% water, dry mass = 6 x 0.05

Amount of duckweeds = 0.3 tons dry mass

The yield of duckweeds is 0.3 tons dry mass / (ha-month).

Example 7.4

Wastewater from a food-processing factory has the following characteristics:

Flow rate = 100 m^3/day
COD = 300 mg/L
BOD_5 = 200 mg/L
NH_4^+ - N = 10 mg/L
PO_4^{3-} - P = 5 mg/L

The factory plans to convert this wastewater to produce protein biomass using the existing pond system that has an area of 1.2 ha. The available alternatives are to grow either water hyacinth or duckweeds. Determine a suitable weed option that will give more financial return annually.

The following information are given:

Water hyacinth

Average stock density = 2 kg/m^2
Area doubling time = 10 days
Protein content = 17% by weight (dry)
Harvesting is done by manually (no addition cost)
Market price of protein = 1 Baht/kg

Duckweeds

Average stock density = 0.7 kg/m^2
Area doubling time = 15 days
Protein content = 20% by weight (dry)
Harvesting cost = 100 Baht/ton dry wt.
Market price of protein = 3 Baht/kg

Note: 1US$ = 40 Baht

a) Water hyacinth

Organic loading of the pond $= 100\left(\frac{m^3}{d}\right)\times 200\left(\frac{mg}{L}\right)\times\frac{10^{-6}kg}{10^{-3}}\times\frac{1}{1.2ha}$

$= 16.66$ kg BOD_5/(ha-day)

Hydraulic loading $= 100\left(\frac{m^3}{day}\right)\times\frac{1}{1.2ha}$ = 83.3 $m^{3/}$(ha-day)

Note: these loading rates are within the ranges reported in Tale 7.9.

Because the doubling time is 10 days, the no. of water hyacinth harvesting is 36 times per year. The amount of water hyacinth harvested is half of the total pond area.

Amount of water hyacinth harvested/year

$= 36 \text{ x } \left(\frac{1}{2}\right) \text{ x } 1.2 \text{ x } 10^4 \text{ x } 2.0 \text{ kg } = 432\text{x}10^3 \text{ kg.}$

Assuming solid content = 5%

Total protein obtained = 0.05 x 0.17 x 432 x 10^3 kg = 3.672 kg.

Income from protein = 1.0 x 3672 = 3672 Baht

Annual income = 3672 Baht

b) Duckweeds

Because the doubling time is 15 days, the frequency of duckweed harvesting is 24 times per year. The amount of duckweeds harvested is half of the total pond area.

Amount of duckweeds harvested per year = $\frac{1}{2}$ x 24 x 0.7 x 1.2x10^4 kg

= 100.8x10^3 kg

Solid content in duckweed = 20%

Total protein obtained = 0.2x0.2x100.8x10^3 = 4032 kg/year

Cost for harvesting = 100.8 x 10^3 x $\frac{0.2\times 100}{1{,}000}$

Income from protein = 4032x3.0 Baht/year

= 12,096 Baht/year

Net income = (12,096 – 2,016) Baht/year

= 10,080 Baht/year

Based on data used in this example, duckweed culture will give more financial return annually.

7.7.5 Emergent aquatic weeds and constructed wetlands

Wetland is an area that is inundated or saturated by surface or groundwater at a frequency or duration sufficient to maintain saturated conditions and growth of related vegetation. Emerged aquatic weeds, such as cattails (*Typhas*), bulrushes (*Scripus*) and reeds (*Phragmaites*) are the major and typical component of the wetland systems (Figure 7.3). Wetland is a natural system where complex physical, biological and chemical reactions essential for wastewater treatment, listed in Table 7.7, exist. To avoid interference with the natural ecosystems, constructed wetland in which hydraulic regime is controlled have been used for treatment of a variety of wastewaters (Hammer 1998; WPCF 1990). Constructed wetlands can range from creation of a marsh land to intensive construction involving earth moving, grading, impermeable barriers, or erection of tanks or trenches (U.S. EPA 1988).

Two types of constructed wetlands have been developed for wastewater treatment, namely, free water surface (FWS) and subsurface flow (SF). An FWS system consists of parallel basins of channels with relatively impermeable bottom and soil and rock layers to support the emergent vegetation, and the water depth is maintained at 0.1 – 0.6 m above the soil surface. An SF system, also called ‘root zone’, or reed bed, consists of channels or trenches with impermeable bottom and soil and rock layers to support the emergent vegetation, but the water depth is maintained at or below the soil surface (Figure 7.18). To reduce the short-circuiting, the length to width ratios of constructed wetlands units should be more than 2:1 and bed slopes of 1 – 5 %. Although it might appear that SF constructed wetlands could be subjected to frequent clogging problems, performance data reported so far have shown them to function satisfactorily with a high degree of removal efficiencies (Reed and Brown 1992 and 1995). An SF constructed wetland can be operated in a vertical flow mode in which wastewater is applied uniformly over the wetland surface and the effluent is collected at the bed bottom. High percentages of BOD and nitrogen removal have been reported from this type of operation (WEF 2001).

Table 7.11 shows removal efficiencies of some constructed wetlands located in the USA, which, in general, are comparable with other constructed wetlands in operation worldwide. Although more than 80 percentage of N and P removal can be expected in constructed wetlands, not much information about the removal of faecal micro organisms is available (see section 7.1.3). Based on the performance data, a summary of wetland design consideration is given in Table 7.12, which should serve as guidelines in the design and operation of natural and constructed wetlands for wastewater treatment.

Table 7.11 Summary of BOD_5 and SS removal from constructed wetlands (U.S. EPA 1988)

Project	Flow, m^3/day	Wetland type	BOD_5 mg/L Influent	BOD_5 mg/L Effluent	SS mg/l Influent	SS mg/l Effluent	% reduction BOD_5	% reduction SS	Hydraulic surface loading rate, m^3/(ha-day)
Listowel, Ontario	17	FWS[a]	56	10	111	8	82	93	-
Santee, CA		SF[b]	118	30	57	5.5	75	90	-
Sydney, Australia	240	SF	33	4.6	57	4.5	86	92	-
Arcata, CA	11,350	FWS	36	13	43	31	64	28	907
Emmitsburg, MD	132	SF	62	18	30	8.3	71	73	1,543
Gustine, CA	3785	FWS	150	24	140	19	84	86	412

[a] Free Water Surface System
[b] Subsurface Flow System

Owing to the complex reactions occurring in wetland beds, it is very difficult to develop a comprehensive model that would adequately describe or predict the treatment efficiency. Nevertheless, Reed and Brown (1995) recommended a first-order reaction for BOD_5 removal in constructed wetlands:

$$\frac{C_e}{C_0} = e^{-k_T . t} \tag{7.11}$$

Where,

C_e = Effluent BOD_5 concentration, mg/L
C_o = Influent BOD_5 concentration, mg/L
k_T = $k_{20}(1.06)^{T-20}$
T = liquid temperature, °C
k_{20} = 1.104 day^{-1}, for SF constructed wetlands,
k_{20} = 0.687 day^{-1} for FWS constructed wetlands
t = hydraulic retention time in the wetland beds, days.

Table 7.12 Summary of wetland design consideration (WPCF 1990). Reproduced by the permission of the Water Environment Federation

Design consideration	Constructed free water surface	submerged bed	Natural
Minimum size requirement, ha/1000 m^3/d	3 – 4	1.2 – 1.7	5- 10
Maximum water depth, cm	50	Water level below ground surface	50; depends on native vegetation
Bed depth, cm	Not applicable	30 – 90	Not applicable
Minimum aspect ratio (L/W)	2:1	Not applicable	Prefer 2:1
Minimum Hydraulic residence time, days	5 – 10	5 – 10	14
Maximum hydraulic loading rate, cm/day	2.5 – 5	6 – 8	1 – 2
Minimum pre treatment	Primary; secondary is optional	Primary	Primary; Secondary; Nitrification, TP Reduction
Configuration	Multiple cells in parallel and series	Multiple beds in parallel	Multiple discharge sites
Distribution	Swale; perforated pipe	Inlet zone (> 0.5 m wide) of large gravel	Swale; perforated pipes
Maximum loading, kg/ha-day			
BOD_5	100 – 110	80 – 120	4
TN	60	60	3
Additional consideration	Mosquito control with mosquito fish; remove vegetation once each 1 to 5 years	Allow flooding capability for weed control.	Natural hydro period should be > 50 %; no vegetation harvest

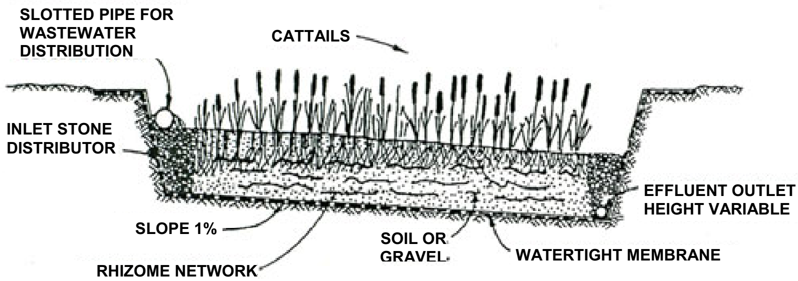

Figure 7.18 Typical cross-section of SF constructed wetlands (U.S. EPA 1988)

It is apparent from the k_{20} values that the SF constructed wetlands are more efficient in the removal of BOD_5 than the FWS constructed wetlands. This superior efficiency is obviously due to better contact between the liquid wastewater and the micro-organisms (mainly bacteria) present in the SF wetland beds responsible for BOD_5 biodegradation, including the filtration and adsorption mechanisms.

It is important to point out that the value of 't' determined from the Equation (7.11) is the time the liquid stays in the void spaces of the constructed wetland beds. Determination of the total bed volume has to include the porosity parameters (γ) as follows:

$$\gamma = V_v/V_t \tag{7.12}$$

$$V_t = Q\,.t/\gamma \tag{7.13}$$

Where,

V_v and V_t = void volume and total bed volume, respectively, m^3.

Q = wastewater flow rate, m^3/day

γ = porosity, unitless

The values of γ for some bed media are given in Table 7.13, which indicate the larger the media diameter, the higher the γ values. Due to the level of free water maintained in the FWS constructed wetlands (10 – 60 cm), their γ values are in the range of 0.65 – 0.75 (WEF 2001).

Since the effect of evapotranspiration (section 7.4) can be significant during the summer and windy periods, the effluent flow rate of a constructed wetland may be much less than that of the influent flow rate. In this respect, the value of Q used in the calculation of V_t (Equation 7.13) should be the average between the influent and effluent flow rates. Depth of a constructed wetland should be deep enough to support the growth of the emergent plant's roots, i.e. about 1.0 – 1.5 m deep.

The cross-sectional area of a SF constructed wetland is calculated as follows (U.S. EPA 1988):

$$A_c = Q/(K_s.S) \tag{7.14}$$

Where,

A_c = cross sectional area of wetland bed perpendicular to the direction of flow (or depth × width), m^2,
K_s = hydraulic conductivity of the medium, $m^3/(m^2\text{-day})$, as given in Table 7.13
S = slope of the wetland bed (as a fraction or decimal)

To ensure the sufficient contact time for wastewater, the value of $K_s.S$ or Q/A_c should be less than 8.6 m/day.

Table 7.13 Typical media characteristics for SF wetlands (WEF 2001)

Media type	D_{10} Effective size [a], mm	Porosity (γ)	K_s, $(m^3/m^{2-}day)$
Coarse sand	2	0.28 – 0.32	100 – 1000
Gravely sand	8	0.30 – 0.35	500 – 5000
Fine gravel	16	0.35 – 0.38	1000 – 10000
Medium gravel	32	0.36 – 0.40	10000 – 50 000
Coarse rock	128	0.38 – 0.35	50000 – 250 000

[a]D_{10} = effective size of the media at 10 % cumulative weight of total, or the size of the media such that 10 % by weight are smaller.

Example 7.5

Compare the area requirements of FWS and SF constructed wetlands (planted with cattails) to be used to treat a wastewater having the following characteristics: average flow rate = 760 m^3/day, influent BOD_5 = 200 g/m^3, and water temperature = 20°C. To meet the discharge standard for reuse, the effluent BOD_5 concentration has to be 10 g/m^3 or less. For FWS constructed wetland: γ = 0.75 and bed depth is 0.7 m (cattail plants root is 0.5 and free water depth is 0.2 m)

For SF constructed wetland: γ = 0.3 and bed depth is 0.5m

Equation 7.11 is applicable to describe the BOD_5 removal efficiency of constructed wetlands.

Solution:
Based on Equation 7.11, determine '*t*' values.

For FWS: $10/200 = e^{-0.678*t}$
$t_{FWS} = 4.4$ days

For SF: $10/200 = e^{-1.104*t}$
$t_{SF} = 2.7$ days

Surface area (A) = $(t*Q)/(d*\gamma)$
$A_{FWS} = (4.4*760) / (0.7*0.75) = 6370\ m^2$
$A_{SF} = (2.7*760) / (0.5*0.3) = 13680 m^2$

To check for hydraulic flow of SF, choose 2 SF units, each with a surface area of 7,000 m^2 or length × width of 100 × 70 m^2. If depth of SF is 1 m, the A_c value is 70 × 1 = 70m^2.

The value of Q/A_c is 380/70 = 5.43 m/day, less than 8.6 m/day.

Note: A_{FWS} and A_{SF} are surface areas of FWS and SF constructed wetlands, respectively. Although the SF constructed wetland has higher k value than the FWS constructed wetland, due to the low porosity (γ) of the bed media, it requires more land area than that of FWS constructed wetland.

Because of current interest in the utilization of constructed wetlands in wastewater treatment/recycling, more comprehensive design models with respect to BOD_5, nutrient and faecal coliform removal that will encompass, not only temperature but also other important parameters, should be developed.

Polprasert *et. al.* 1998 applied a dispersed flow model incorporating biofilm activity (similar to Equation 7.5) to describe organic removal efficiency of a FWS constructed wetlands with satisfactory results. They also found the biofilm activity to be several times more significant in organic removal than the suspended bacterial activity in the FWS constructed wetland bed.

From their surveys of more than 20 constructed wetlands sites in the USA, Reed and Brown (1992) did not observe the need of annual harvesting of the common emergent vegetation, but recommended that the vegetative detritus present in the wetland beds be cleaned out on some extended schedule. However, because vegetative plants obviously grow faster in the tropics than in temperate climates, it would be useful to study the need and frequency of plant harvesting for constructed wetlands located in tropical areas in accordance with the area doubling time, as discussed in section 7.4. When subjected to frequent harvesting, Sawaittayothin and Polprasert (2006) found N uptake by cattail plants to be 80% of the total N input when they were cultured in a SF constructed wetlands located in the tropics. The plant productivity was accordingly high and beneficial for reuses.

7.8 HEALTH HAZARDS RELATING TO AQUATIC WEEDS

The cultivation of aquatic weeds may cause health problems by:

- Contamination of the people who work in the aquatic pond operation with pathogens in the water,
- Contamination of the plants with pathogens and toxic materials such as heavy metals and pesticides, and
- Providing habitats (pond & plants) for various vectors.

Concerning the first and second health problems, the risk of contacting pathogens by workers and contamination of plants with pathogens can be minimized if the waste is adequately treated to eliminate pathogens before applying to aquatic plants. This step is necessary as pathogen removal in an aquatic system is not very effective. Direct fertilization of aquatic weed ponds with nightsoil should be avoided as the risk is high and it reduces the acceptability of the product.

The third health problem involves the possibility of disease transmission through infection by metacercariae, (infective stage) which has its intermediate host in the pond, such as snails (in case of *Schistosomiasis*) or attached to the plant leaves and stems. According to Feachem *et al.* (1983), the parasitic fluke *Fasciolopsis buski* is important in some parts of Asia. The worm has a life cycle that moves from man (or pig or dog) to snail to water plant and then to man again. Animals or people become infected by eating the encysted metacercariae on water plants, such as seed pods of water caltrop, bulbs of water chestnut, and roots of lotus, water bamboo, etc. In cases where those diseases associated with intermediate hosts in the pond are endemic and their respective hosts are present in that area, waste recycling using aquatic plants is not advisable.

Aquatic vegetation enhances the production of mosquito by protecting the larvae from wave action, providing a habitat for breeding and interfering with mosquito control procedures. The two major vectors are *Anopheles* that transmits malaria, and *Mansonia* that carries filariasis and encephalitis.

The eggs of *Mansonia* are laid on the undersides of leaves of aquatic weeds just above the surface of the water. The mosquito larvae inserts it's respiratory siphon into the air-containing tissues of the plant and need not come to the surface of water for air. The air is obtained from the submerged portions of the plant, especially from the roots. Different *Mansonia* species have a preference for certain plants but water lettuce seems to be the most common host, followed by water hyacinth then *Azolla* and duckweeds.

An effective way to prevent breeding of mosquito in the pond is to stock fish that feed on mosquito larvae. Successful control was reported by culturing fish *S. Mossambicus* in water spinach ponds and *Gambusia affinis* in water hyacinth ponds (Edwards 1980; Wolverton *et al.* 1975).

Biological accumulation in aquatic weeds will occur when wastewater containing pesticides and heavy metals are treated, thus reducing their potential as food and as for agricultural purposes. Wastewaters containing toxic materials should be pretreated to remove these specific contaminants or other alternatives for treatment and recovery has to be considered.

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7.10 EXERCISES

7.1 From Equations 7.1 and 7.2, derive the following equation:

$$\text{Doubling time} = \frac{\ln 2}{\ln x}$$

where x = daily incremental factor.

7.2 It is estimated that water hyacinths have a doubling time of 10 days in natural freshwater. Determine how much time is needed for initially 10 water hyacinth plants to cover 0.4 ha of a natural freshwater surface The average density of water hyacinths in water bodies is about 150 plants/m^2.

7.3 Design a constructed wetland system to treat a raw wastewater with the following characteristics:

Flow rate	= 500 m^3/day
BOD_5	= 200 mg/L
COD	= 300 mg/L

The effluent BOD_5 concentration after treatment should be less than 10 mg/L.

Give reasons about the types of constructed wetlands you plan to choose, and draw schematic diagram of the constructed wetlands including the hydraulic profiles.

7.4 A rural household plans to build a 200 m^2 fish pond to raise Tilapia. It intends to grow duckweeds as fish feed. To produce a fish yield of 110 kg/pond/yr, a duckweed loading of 4 kg dry weight per pond per day is needed. If the doubling time of duckweed is 10 days, determined the required area of the duckweed pond. Assume an average duckweed density of 8 kg (wet weight)/m^2 and a moisture content of 94% for duckweeds.

7.5 You are to visit a floating aquatic weed pond and a constructed wetland unit being used for wastewater treatment, and determine the first-order k_T values, as shown in Equations 7.4 and 7.11, respectively. Compare the results and discuss whether the k values of these two systems should be the same or different.

7.6 If you are to modify Equations 7.4 and 7.11 to encompass other parameters responsible for wastewater treatment in constructed wetlands or floating aquatic weed ponds, what are the parameters to be included and how are these equation to be modified?

7.7 An international space station (ISS) has 10 astronauts and is producing total wastewater with the following characteristics:

Flow rate	= 1 m^3/day
BOD_5	= 200 g/m^3
Fecal coliforms	= 10^3 no./100 mL

Assuming that a floating-aquatic-plant system, employing water lettuce (*Pistia stratiotes*), is to be used to treat this wastewater on the ISS at the organic loading rate of 100 kg BOD_5/(ha-day) and hydraulic retention time of 5 days.

a) Based on the data given in Figure 7.15, determine the dimension (length × width × depth) required for the floating-aquatic-plant system to be built on the ISS and the BOD_5 concentration of the treated effluent. Draw a schematic diagram of this wastewater treatment system to be installed in the ISS and suggest a possible method to reuse this treated wastewater in the ISS. *Note:* Assuming that sunlight is sufficient at the ISS for plant growth, but there is no gravitational force.

b) Assuming an optimum density of the water lettuce is 20 kg (wet weight)/m^2, water content of the water lettuce is 90%, and the area doubling time of water lettuce is 20 days. Determine the monthly productivity of the water lettuce from this wastewater treatment system. Can this harvested water lettuce from this wastewater treatment system be consumed by the astronauts and why? The WHO microbiological guidelines for wastewater reuse is given in Table 2.28.

7.8 A university campus in central Asia produces wastewater with the following characteristics:

Flow rate	= 3,000 m^3/day
BOD_5	= 150 g/m^3
Fecal coliforms	= 10^6 no./100 mL
Temperature	= 25°C

It is required that the above wastewater be treated to attain the effluent BOD_5 and fecal coliform standards of 20 g/m^3 and 10^3 no./100 mL, respectively, suitable for discharging to the nearby canal.

a) Determine the dimension (length × width × depth) of a subsurface flow (SF) constructed wetlands that needs to be constructed to achieved the above requirements of BOD_5 and fecal coliform reduction. The following information about SF constructed wetlands and cattail plants are :

Bed porosity	= 0.3
Depth of cattail roots	= 0.5 m
Evapotranspiration	= 50% of influent wastewater

Removal of BOD_5 and fecal coliforms in SF constructed wetlands follow Equation 7.11

b) Suppose the same SF constructed wetland in (a) is converted to become free-water-surface (FWS) constructed wetland by raising the effluent outlet pipe to be 10 cm above the constructed wetland bed. The bed porosity of the FWS constructed wetlands is 0.7, while the value of k_{25} for BOD_5 and fecal coliform removal are 0.7 and 1.6 day^{-1}, respectively, for use in Equation 7.11

Determine whether the effluent BOD_5 and fecal coliform concentrations of the FWS construct wetlands will meet the required standards or not and why?

7.9 A small municipality in Southeast Asia produces wastewater with the following characteristics:

Flow rate	= 100 m^3/day
BOD_5	= 200 g/m^3
NH_4-N	= 20 g/m^3
Fecal coliforms	= 10^4 no./100 mL

The municipality plans to construct a water hyacinth-based pond to treat this wastewater and reuse the treated wastewater for fish production.

a) Determine the dimension of the water hyacinth-based pond to treat this wastewater that should produce an effluent having BOD_5 and NH_4-N concentrations of less than 20 and 5 g/m^3, respectively. Indicate whether the treated wastewater is suitable to be applied to fish ponds.
b) If the area doubling time of the water hyacinth plants is 20 days and density of the water hyacinth plants growing in this pond is 4 kg (wet weight) per m^2, determine: (1) the monthly quantity of water hyacinth plants that needs to be harvested to maintain optimum pond performance and (2) the annual productivity of the water hyacinth plants.

For BOD_5 removal in water hyacinth-based ponds: recommended BOD_5 loading rate = 100 kg/(ha-day) and the BOD_5 removal follows the data given in Figure 7.15.

For NH_4-N removal in water hyacinth-based ponds: NH_4-N removal follows Equation 7.10.

8

Land treatment of wastewater

Land treatment is defined as the controlled application of wastes on to the land surface to achieve a specified degree of treatment through natural physical, chemical and biological processes within the plant-soil-water matrix.

Land treatment of wastewater has been practiced for long time and it has received considerable attention nowadays as an alternative treatment to other existing treatment processes. In developing countries, where land is plentiful, land treatment is considered as a less expensive treatment method.

8.1 OBJECTIVES, BENEFITS, AND LIMITATIONS

In the past, the objective of land treatment was simply to dispose of the wastes, but the current trend of this practice has included the utilization of nutrients in the wastewater and sludge for crop production and tertiary (advanced) treatment of wastewater or to recharge groundwater.

Wastewater disposal on land will be a viable treatment method only if the protection of groundwater from possible degradation is held as a prime objective. With the treatment of wastewater, other benefits such as economic return from marketable agricultural crops, exchange of wastewater for irrigation purposes in arid climates to achieve overall water conservation, and development and preservation of open space and green belts can also be obtained from land treatment process.

Land treatment systems are less energy intensive than conventional systems. (Examples of conventional systems include activate sludge, trickling filters and aerated lagoons, etc.) In land treatment, energy is needed for transportation and application of wastewater to the land. But in conventional treatment systems such as activated sludge, energy is needed for transportation of wastewater, mixing and aeration of wastewater and sludge, return sludge, effluent recirculation, and transportation of digested sludge.

Since less mechanical equipments are needed for land treatment process when compared with other conventional treatment processes, the maintenance of the land treatment system is easy and less expensive.

However, land area, soil condition and climate are the main limiting factors of this treatment process. Large area of land is normally required for application of wastewater; for some cities, these land treatment sites may be too expensive or too far away from the wastewater sources. Soil condition is important for the removal mechanisms of wastewater constituents, and a soil having too coarse or too fine texture is not appropriate for land treatment. Climate conditions where the magnitude of evaporation and evapotranspiration is greater than that of precipitation are generally preferred for land treatment of wastewater and sludge.

8.2 WASTEWATER RENOVATION PROCESSES

Depending on the rate of water movement and the flow path within the process, the treatment of wastewater by land is classified as:

- Slow rate (or irrigation) process (SR),
- Rapid infiltration process (RI), and
- Overland flow process (OF)

Selection of process depends on the required objectives as well as the soil condition of the land. Figure 8.1 gives the relationship between loading rate, and soil type for the above three processes. A description of soil textural classes is given in Table 8.1.

A comparison of design features for alternative land treatment processes is shown in Table 8.2 and the expected quality of treated wastewater from land treatment processes are given in Table 8.3. The site characteristics for the land treatment processes are comparatively shown in Table 8.4. Excellent effluent quality is usually obtained with land treatment systems (Table 8.3) because the

BOD_5 loadings applied (Table 8.2) are much lower than the BOD_5 removal capabilities. Design of a land treatment system is based generally on hydraulic application rates and nitrogen loadings. However, BOD_5 loading to a land treatment site needs to be carefully evaluated so that anaerobic conditions do not occur. The occurrence of anaerobic conditions is usually harmful to the root system of crops and affecting the availability of nutrients to the crop; it may also enhance mobility of toxic materials previously precipitated there.

Table 8.1 Soil texture classes and general terminology used in soil descriptions (U.S. EPA 1981)

General terms		Basic soil textural class names
Common names	Texture	
Sandy Soil	Coarse	Sandy
		Loamy sand
	Moderately coarse	Sandy loam
		Fine sandy loam
Loamy soils	Medium	Very fine sandy loam
		Loam
		Silt loam
		Silt
	Moderately fine	Clay loam
		Sandy clay loam
		Silty clay loam
Clayey soils	Fine	Sandy clay
		Silty clay
		Clay

8.2.1 Slow rate process (SR)

SR is the controlled application of wastewater to a vegetated land at a rate of a few centimetres of liquid per week. The flow path depends on infiltration, and usually lateral flow within the treatment site. Treatment occurs by means of physical, chemical and biological processes at the surface as the wastewater flows through the plant-soil matrix. A portion of the flow may reach the groundwater, some is used by the vegetation, but off-site runoff of the applied wastewater is avoided by the proper system design. Typical hydraulic pathways for SR treatment are shown in Figure 8.2 (a) in which surface vegetation responsible for evapotranspiration and soil percolation is essential components in this treatment process. The percolated water can be collected through underdrains placed under the vegetation soil or from the recovery wells constructed within the vicinity.

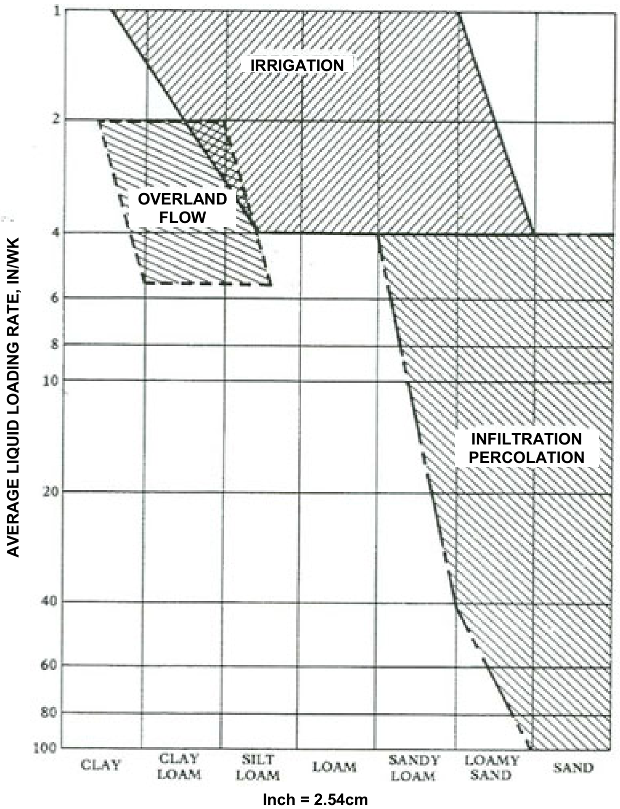


Figure 8.1 Soil type vs liquid loading rates for different load application approaches (U.S. EPA 1976)

The objectives of SR process are: treatment of the applied wastewater; conservation of water through irrigating landscaped areas; and economic gain from the use of wastewater and nutrients to produce marketable crops.

The principal limitations to the practice of SR are: the considerable land area required, its relatively high operating cost, and the treatment site is usually long distance away from the wastewater sources. As shown in Figure 8.1 and Table 8.1, wastewater application rates for SR are smaller than the other two land treatment processes. The SR application rates vary from 2.5-10 cm/week depending on the types of crops and soil. In some cases, certain wastewater characteristics, such as high salt and boron concentrations, may preclude irrigation of many crops, especially in the arid regions.

Table 8.2 Comparison of typical design features for land treatment processes (U.S. EPA 1981)

Features	Slow rate	Rapid infiltration	Overland flow
Application techniques	Sprinkler or surface[a]	Usually surface	Sprinkler or surface
Annual loading rate, m	0.5 – 6	6 – 125	3 – 20
Field area required, ha[b]	23 – 280	3 – 23	6.5 – 44
Typical weekly loading rate, cm	1.3 – 10	10 – 240	6 – 40[c]
Minimum preapplication treatment provided in the United States	Primary sedimentation[d]	Primary sedimentation[e]	Grit removal and comminution[e]
Disposition of applied wastewater	Evapotranspiration and percolation	Mainly percolation	Surface runoff and evapotranspiration with some percolation
Need for vegetation	Required	Optional	Required
BOD_5 loading[f] kg/ (ha-year)	370-1,830	8,000–46, 000	2,000–7,500

[a] Includes ridge-and-furrow and border strip.
[b] Field area in hectares not including buffer area, roads, or ditches for 3,785 m^3/day (1 mgd) flow.
[c] Range includes raw wastewater to secondary effluent, higher rates for higher level of preapplication treatment.
[d] With restricted public access; crops not for direct human consumption.
[e] With restricted public access.
[f] Range for municipal wastewater.

Adequately disinfected wastewater should pose no danger to health when it is used for irrigation. Adequate disinfection, which can be very costly, requires complete and rapid mixing and a specified contact time of the disinfectant in the effluent. Any aerosolising of inadequately disinfected water produces possible health risks to human, and these risks should be minimized. Before harvesting of the irrigated crops, wastewater application must be stopped to allow for drying of the soil and die-off of the pathogens that may be present on the crops.

Table 8.3 Expected quality of treated water from land treatment processes[a] (U.S. EPA 1981)

Constituents	Slow rate[b]		Rapid infiltration[c]		Overland flow[d]	
	Average	Upper range	Average	Upper range	Average	Upper range
BOD_5	< 2	<5	5	<10	10	<15
Suspended solids	<1	<5	2	<5	10	<20
Ammonium nitrogen as N	<0.5	<2	0.5	<2	<4	<8
Total nitrogen as N	3[e]	<8[e]	10	<20	5[f]	<10[f]
Total phosphorus as P	<0.1	<0.3	1	<5	4	<6
Fecal coliforms, no/100 ml	0	<10	10	<200	200	<2,000

Units in mg/L unless otherwise noted
[a] Quality expected with loading rates as the mid to low end of the range shown in Table 8.2.
[b] Percolation of primary of secondary effluent through 1.5 m (5 ft) of unsaturated soil.
[c] Percolation of primary or secondary effluent through 4.5 m (15 ft) of unsaturated soil; phosphorus and fecal coliform removals increase with distance of wastewater flow.
[d.] Treating comminuted, screened wastewater using a slope length of 30-36 m (100-120 ft).
[e] Concentration depends on loading rate and crop.
[f] Higher values expected when operating through a moderately cold winter or when using secondary effluent at high rates.

In general maximum cost effectiveness for both municipal and industrial wastewater systems will be achieved by applying the maximum possible amount of wastewater to the smallest possible land area. This will in turn limit the choice of suitable vegetation and possibly the market value of the harvested crop. Optimization of a system for wastewater treatment usually results in the selection of perennial grasses because of the longer application season, higher hydraulic loadings, and greater nitrogen uptake, compared to other agricultural crops. Annual planting and cultivation can also be avoided with perennial grasses.

Forest systems also offer the advantage of a longer application season and higher hydraulic loadings than typical agricultural crops, but may be less efficient than perennial grasses for nitrogen removal depending on the type of tree, its stage of growth and the general site conditions.

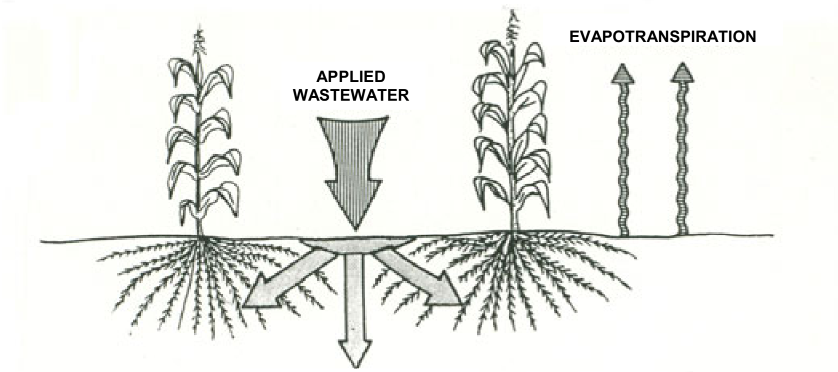
Methods of irrigation

Spray, ridge and furrow, and flood are the wastewater irrigation methods commonly adopted in this process (Figure 8.2). Spray irrigation may be accomplished by using a variety of systems from portable to solid-set sprinklers (Figure 8.2c). Ridge and furrow irrigation consists of applying water by gravity flow into furrows. The relatively flat land is groomed into alternating ridges and furrows with crops grown on the ridges (Figure 8.2b). Flood irrigation is accomplished by inundation of land with water. The type of irrigation system to be used depends upon the soil drainability, the crop, the topography, process objective and the economics. Table 8.5 gives the methods of surface irrigation (flood and ridge and furrow) and their conditions of use applicable for wastewater and other irrigation water.

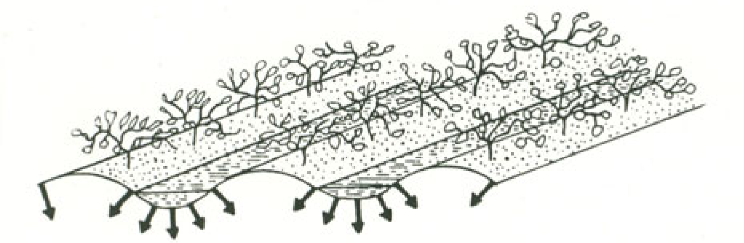
Table 8.4 Comparison of site characteristics for land treatment processes (U.S. EPA 1981)

	Slow rate	Rapid infiltration	Overland flow
Grade	Less than 20 % on cultivated land; less than 40 % on non-cultivated land	Not critical; excessive grades require much earthwork	Finish slopes 2- 8 %
Soil permeability	Moderately slow to moderately rapid (clay loam to sand loam), > 0.15 cm/h	Rapids (sands, sandy loams), >5.0 cm/h	Slow (clays, silts and soil with impermeable barriers), < 0.5 cm/h
Depth to groundwater	0.6 – 1 m (minimum)[b]	1 m during flood cycle;[b] 1.5 – 3 m during drying cycle	Not critical
Climatic restrictions	Storage often needed for cold weather and during heavy precipitation	None (possibly modify operation in cold weather)	Storage usually needed for cold weather

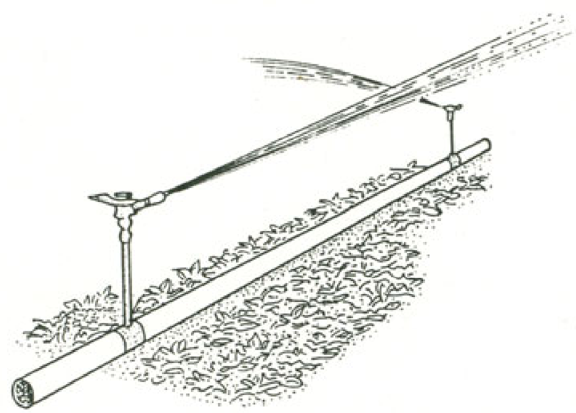
[a] Steeper grades might be feasible at reduced hydraulic loadings.
[b] Under drains can be used to maintain this level at sites with high ground water table.
[c] Impact on ground water should be considered for more permeable soils.



a) Hydraulic pathway



b) Surface distribution



c) Sprinkler distribution

Figure 8.2 Slow-rate land treatments (U.S. EPA 1981)

Table 8.5 Surface irrigation methods and conditions of use

	Suitabilities and conditions of use				
Irrigation methods	Crops	Topography	Water quantity	Soils	Remarks
Flooding					
Small rectangular basins	Grains, field crops, orchards, rice	Relatively flat land; area within each basin should be levelled.	Can be adapted to streams of various sizes	Suitable for soils of high or low intake rates; should not be used on soils that tend to puddle	High installation costs Considered labour required for irrigations When used for close-spaced crops a high percentage of land is used for levees and distribution of water use possible.
Large rectangular basins	Grains, fild crops, rice	Flat land; must be graded to uniform plane.	Large flows of water	Soils of fine texture with low intake rates	Lower installation costs and less labour required for irrigation than small basins. Substantial levees needed.
Contour check	Orchards, grains, rice, forage crops	Irregular land, slopes less than 2%	Flows greater than 1 ft^3/s	Soils of medium to heavy texture that do not crack on drying	Little land grading required. Checks can be continuously flooded (rice), water ponded (orchards), or intermittently flooded (pastures)

Table 8.5 Surface irrigation methods and conditions of use (continued)

Irrigation methods	Suitabilities and conditions of use: Crops	Topography	Water quantity	Soils	Remarks
Wide borders up to 100 ft wide	Grains, alfalfa, orchards	Land graded to uniform plane with maximum slope less than 0.5%	Large flows up to 20 ft^3/s	Deep soils of medium to fine texture	Very careful land grading necessary Minimum of labour required for irrigation Little interference with use of farm machinery
Furrows					
Straight furrow	Vegetables, row crops, orchards, vineyards	Uniform slopes not exceeding 2 % for cultivated crops	Flows up to 12 ft^3/s	Can be used on all soils if length of furrows is adjusted to type of soil.	Best suited for crops that cannot be flooded. High irrigation efficiency possible. Well adapted to mechanized farming.
Graded contour furrows	Vegetables, field crops, orchards, vineyards	Undulating land with slopes up to 8%	Flows up to 3 ft^3/s	Soils of medium to fine texture that do not crack during drying	Rodent control is essential. Erosion hazard from heavy rains or water breaking out of furrows. High labour requirements for irrigation.

Table 8.5 Surface irrigation methods and conditions of use (continued)

	Suitabilities and conditions of use				
Irrigation methods	Crops	Topography	Water quantity	Soils	Remarks
Corrugations	Closed-spaced crops such as grain, pasture, alfalfa	Uniform slopes of up to 10 %	Flows up to 1 ft^3/s	Best on soils of medium to fine texture	High water losses possible from deep percolation or surface runoff. Care must be used in limiting size of flow in corrugations to reduce soil erosion. Little land grading required.
Basin furrows	Vegetables, cotton, maize, and other row crops	Relatively flat land	Flows up to 5 ft^3/s	Can be used with more soil types	Similar to small rectangular basins, except crops planted on ridges
Zigzag furrows	Vineyards, bush, berries, orchards	Land graded to uniform slopes of less than 1 %	Flows required are usually less than for straight furrows	Used on soils with low intake rates	This method is used to slow the flow of water in furrows to increase water percolation into soil

1 $ft^3/s = 0.028\ m^3/s$; 1 ft = 0.305 m From Booher (1974); reproduced by the permission of the Food and Agriculture Organization of the United Nations.

Reliability

As shown in Table 8.3, a high-quality effluent can be expected from SR process. For a well-operated SR system, treatment efficiency is in the order of 99% for BOD_5, suspended solids, and fecal coliforms. As irrigation soils are loamy (see Figure 8.1), considerable amounts of organic matter, heavy metals, phosphorus, and microorganisms are retained in the soil by adsorption and other mechanisms. It should be noted that plant uptake and/or adsorption of heavy metals and pathogens are a potential problem in the reuse of these irrigated plants. Nitrogen is up taken by plant growth and if the crop is harvested, the removal rate can be in the order of 90%.

Site selection

Soils ranging from clay loams to sandy loams are suitable for irrigation (Figure 8.1). Soil depth should be at least 0.3 m of homogeneous material and preferably 1.5 to 2 m throughout the site. The depth is needed for extensive root development of some plants and for wastewater renovation. The minimum depth to groundwater should be 0.6-1.0 m to avoid groundwater contamination (Table 8.4). If the site drainage is poor, control procedures such as under drains or wells may be required. For crop irrigation, slopes should be limited to 20% or less depending upon the type of farm equipment to be used. Forested hillsides and non-cultivated land up to 40% in slope have been spray irrigated successfully (Table 8.4).

8.2.2 Rapid infiltration process (RI)

RI is the controlled application of wastewater to earthen basins in rapidly permeable soils (e.g. sandy loam, loamy sand and sand) at a high rate (Figure 8.1). Treatment is accomplished by biological, chemical and physical interactions in the soil matrix with the near surface layer being the most active zone. The design flow path requires infiltration, and typically lateral flow away from the application site. A cyclic application is the typical mode of operation with the flooding period followed by the drying period. This allows aerobic restoration of the infiltration surface and drainage of the applied percolate. The geo-hydrological aspects of the RI site are more critical than for other processes. Proper subsurface conditions and the local groundwater system are essential for design. Schematic views of the typical hydraulic pathways for RI process are shown in Figure 8.3. A much greater portion of the applied wastewater percolates to the groundwater than with slow rate land treatment. The percolated water is collected for reuse by under drains or recovery wells (Figure 8.3 b & c).

In some cases, the percolated water can move through underground aquifers into surface streams nearby.

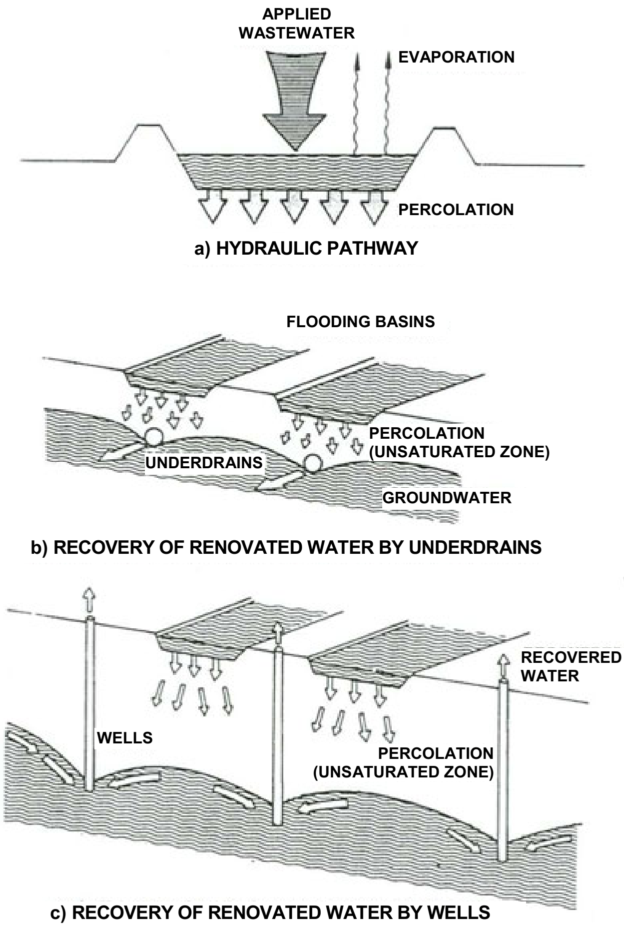


Figure 8.3 Rapid infiltrations (U.S.EPA 1981)

The main objective of a rapid infiltration system is wastewater treatment, and the system design and operating criteria are developed to achieve this goal. However, there are other objectives with respect to the utilization or final disposal of the treated water. They are:

- Groundwater recharge
- Recovery of treated water for subsequent reuse or discharge
- Recharge of surface streams
- Seasonal storage of treated water beneath the site with recovery and agricultural reuse during the growing season.

The wastewater is applied to rapidly permeable soils by spreading in basins or by sprinkling, and is treated as it travels through the soil matrix. Vegetation is not usually used, but there are some exceptions.

Advantages of this process are: it is a treatment system with nearly complete recovery of renovated water; and it is a method of repelling salt-water intrusion into the aquifers. Where ground water quality is being degraded by salinity intrusion, groundwater recharge can be used to reverse the hydraulic gradient and protect the groundwater.

The limitations of this process are in connection with groundwater effects: influent nitrogen may be converted to the nitrate form, which is leached to the groundwater; if the zone becomes anaerobic or anoxic, conversion of sulphates to hydrogen sulfide may be a problem; and phosphorus retention in the soil matrix may be neither complete nor of long duration.

Reliability

Removal of constituents by the filtering and straining action of the soil is effective. Suspended solids, fecal coliforms, and BOD_5 are almost completely removed in most cases. Nitrogen removal is generally about 50%, unless specific operating procedures are established to maximize denitrification. Phosphorus removals range from 70 to 95% depending on the physical and chemical characteristics of the soil that influence retention of phosphorus.

Site selection

Acceptable soil types include sand, sandy loams, and loamy sand (Figure 8.1). Very coarse sand and gravel is not ideal because it allows wastewater to pass too rapidly through the upper few cm of soil where biological and chemical actions take place. Other factors include percolation rate, depth, movement and quality of groundwater, topography and underlying geological formations.

8.2.3 Overland flow process (OF)

A schematic view of overland flow treatment including a pictorial view of a typical OF sprinkler system is shown in Figure 8.4.

OF is a treatment method in which wastewater is applied over the upper reaches of sloped terraces and allowed to flow across the vegetated surface to runoff collection ditches. The objectives of OF process are: (1) to treat the wastewater to a degree comparable to that of secondary or tertiary treatment and (2) to produce forage grasses or preserving greenbelts and open space. OF is subject to the same type of limitations as SR, but it can be applied to relatively impermeable soil and a gently sloping terrain. The technique has considerable potential for treatment of municipal wastewater. The effluent is of a quality approaching that from tertiary treatment. In addition to a low construction cost, the system produces little or no sludge, which is convenient for the system's operation and maintenance.

Operating costs are considerably lower than the conventional and advanced waste treatment because of the relative simplicity of operation. It has the advantages of avoiding groundwater degradation, providing economic return through the growth and sale of hay, and providing a high quality effluent suitable for industrial or agricultural reuse. Sodium effects (discussed in section 8.3) on overland flow systems are less critical because the infiltration rates of the soils are low.

Reliability

Overland flow systems at various places using wastewater have been monitored to determining removal efficiencies. The expected ranges based on results at these sites are BOD_5 and SS removal of 95 to 99%, nitrogen removal of 70 to 90%, and phosphorus removal of 50 to 60% (see Table 8.3). Biological oxidation, sedimentation, and grass filtration are the primary removal mechanisms for organics and suspended solids. Nitrogen removal mechanisms include crop uptake, biological uptake, denitrification, and fixation in soil. Phosphorus is removed by adsorption and precipitation.

Site selection

Soils with limited drainability, such as clay and clay loams are suitable for OF system (Figure 8.1). The land may have a slope between 2 to 8% and a very smooth surface so that the wastewater will flow in a sheet over the ground surface. Grass is planted to provide a habitat for the bacteria to stabilize the wastewater and for further use as animal feeds. Because groundwater will not likely to be affected, it is of little concern in site selection.

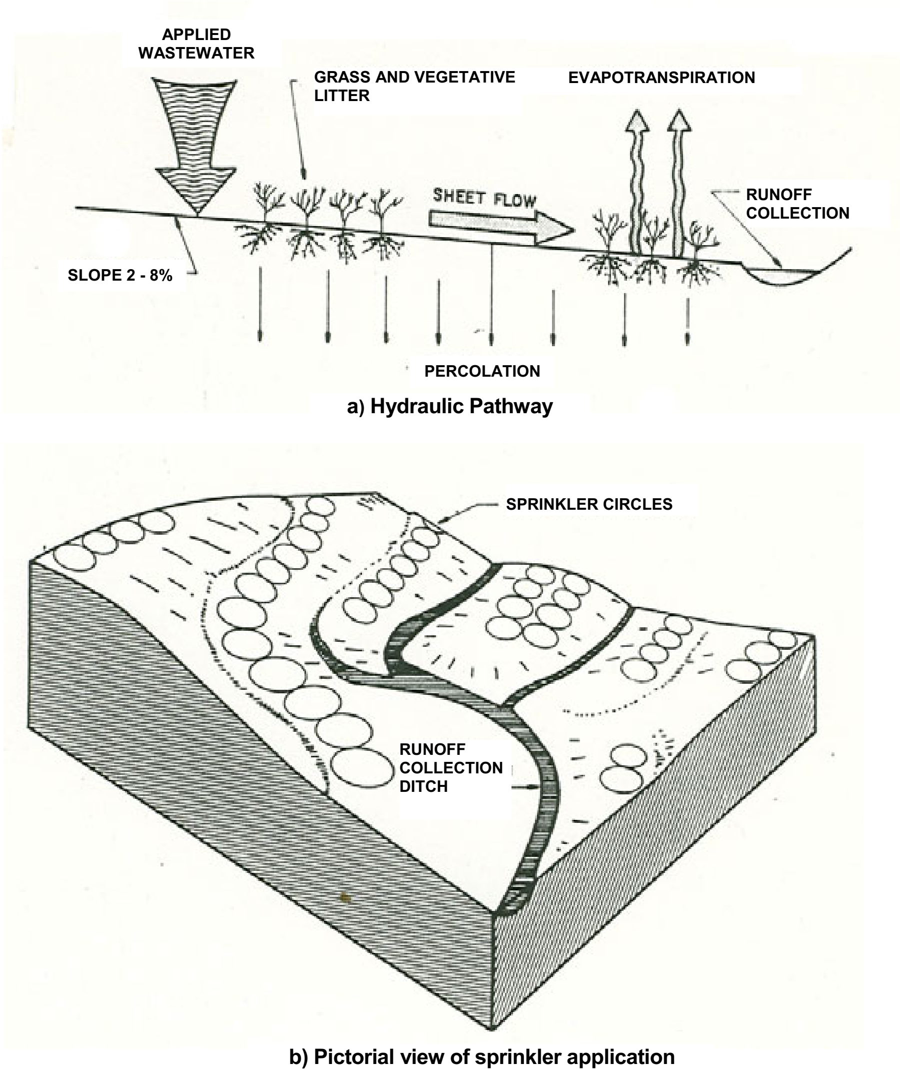


Figure 8.4 Overland flow (U.S.EPA 1981)

8.2.4 Combined processes

Rapid infiltration can be used after overland flow to further reduce concentrations of BOD_5, suspended solids, and phosphorus. Because of the increased reliability and overall treatment capability, the application rates for the overland flow process could be higher than normal. This is shown schematically in Figure 8.5 (a).

In another scheme, Figure 8.5 (b), the rapid infiltration process precedes slow rate treatment. The recovered renovated water should meet even the most restrictive requirements for use on food crops. The unsaturated zone can be used for storage of renovated water to be withdrawn on a schedule consistent with crop needs.

8.2.5 Groundwater recharge

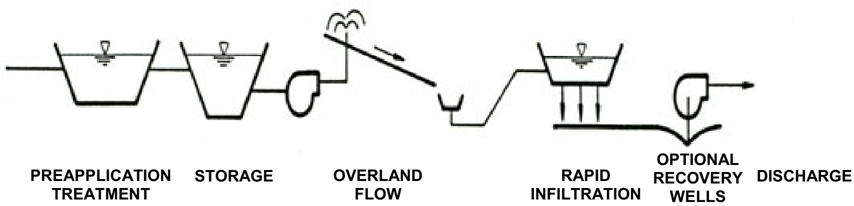
Recharging underground aquifers with treated wastewater is one of the generally accepted forms of water reuse. The water disappears from the site and is usually diluted by other sources of water. Furthermore, a long time ordinarily elapses before recharged water is extracted, so most microbial contaminants will die off. Basically, there are two different methods for recharging an aquifer. Either water may be allowed to enter the aquifer from the surface through spreading beds or spray irrigation, or it may be pumped under pressure through to down wells which will penetrate a deep aquifer.

Water applied to the soil surface will be filtered and biologically oxidised, and many chemical constituents will be adsorbed or precipitated on the soil particles. The treatment given by surface infiltration can be equivalent to, or better than, conventional biological treatment followed by filtration and disinfection.

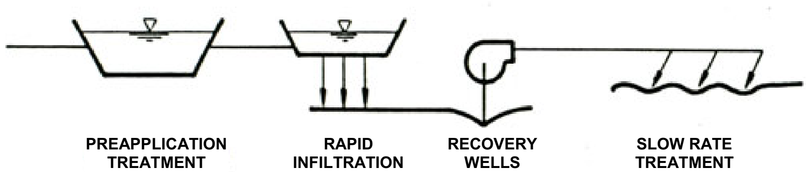
8.3 WASTEWATER RENOVATION MECHANISMS

Any wastewater treatment system, including a land treatment system, is designed to convert the wastewater into an acceptable effluent and to dispose of the solids removed and produced in the system. The basic approach is to determine the characteristics of the untreated waste and to utilize the capabilities of various treatment processes to achieve the desired effluent quality.

The effectiveness of a land treatment system is related to the characteristics of the soil and the resultant pollutant removal mechanisms. When wastewater is applied to the soil, some constituents may pass through the soil to the groundwater, some are utilized by growing plants, some are metabolized by the soil micro-organisms, and others are retained within the soil. The design of a wastewater land treatment system and the need for pre-application (or pre-treatment) methods must relate the quantity and types of pollutants in the wastewater to the pollutant removal mechanisms in the soil. These can be categorized as physical, such as gravitational settling, filtration and dilution; chemical, such as adsorption and precipitation; and biological, such as microbial transformations and plant uptake. The need for pre-application can be determined by evaluating the possibility of overloading the removal mechanisms.



(a) Overland flow followed by rapid filtration



(b) Rapid infiltration followed by slow rate treatment

Figure 8.5 Examples of combined systems (U.S.EPA 1981)

The waste management relationship that occurs with land treatment of wastewater is shown in Figure 8.6.

8.3.1 Physical removal mechanisms

As wastewater moves through the soil pores, suspended solids are removed by filtration. The depth at which removal occurs varies with the size of the particles, soil texture, and rate of water movement. The higher the hydraulic application rate and the coarser the soil, the greater the distance the particles will move. However, at the wastewater application rates used with the slow rate process, large suspended solids are removed in the surface soil and smaller particulates including bacteria are removed in the upper few centimeters of most soils, except the very coarse soils.

Constituents in the applied wastewater can be diluted by rain and, for cold climates, snowmelt. Chemical and biological transformations and removals in the soil also can reduce concentrations of specific constituents. Where evaporation losses are high, as in arid climates, increases in the concentration of conservative constituents such as salts can occur.

Excessive suspended solids can clog the soil pores as well as the wastewater distribution systems. Clogging of the soil will reduce the soil infiltration rate. Natural decomposition of the organic solids during non-application of wastewater or "resting" periods will allow the infiltration rate to recover.

The design hydraulic application rate for a land treatment system should be less than the infiltration rate of the soil. At this application rate, soil clogging due to suspended solids will not be a significant problem. Thus preapplication methods for suspended solids removal should be limited to methods such as screening or primary sedimentation that will avoid clogging of the irrigation distribution equipment or avoid excessive wear of pumps and piping.

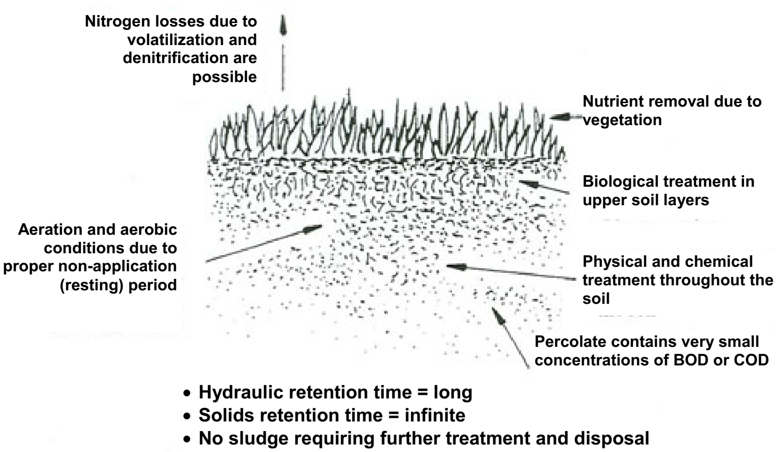


Figure 8.6 Waste management relationships that occur with land treatment (from Loehr and Overcash 1985; reproduced by the permission of the American Society of Civil Engineers)

8.3.2 Chemical removal mechanisms

Chemical reactions in the soil affect the mobility of dissolved ions or compounds with the result that some constituents are retained within the soil profile for extended periods of time while the movement of others may only be temporarily restricted. Liquid residence times for normal wastewater irrigation rates are on the order of weeks, while some constituents may be retained in the soil for a much longer period.

Adsorption and chemical precipitation are the most important chemical reactions governing the movement of constituents in the irrigated wastewater with cation exchange being the most important adsorption phenomenon. The cation exchange capacity (CEC) of soils can range from 2 to 60 meq/100 g of soil, with most soils having a CEC value between 10 and 30. The differences occur because soils vary widely in their humus and clay content, the components that have the highest CEC.

Typical soils have considerable capacity to adsorb many of the cations in wastewater, including many of the metals, which may adversely affect the health of human and animals eating the crops grown on the irrigated fields.

Cation exchange of ammonium nitrogen is a possible control mechanism for nitrogen. However, the ammonium ion is biologically oxidized to nitrate in aerobic soils. Nitrate is an anion and will move with the soil water.

Phosphate is the only anion appreciably retained in soil. The primary mechanism is the formation of insoluble or slowly soluble precipitates.

In arid regions, wastewater irrigation rates may not be enough to avoid the accumulation of sodium ions in the soil. Such accumulations can lead to a degradation of soil structure and reduction in water percolation rates.

The relationship between the principal cations in wastewater (calcium, magnesium, sodium, and potassium) is of importance. When the ratio of sodium to the other cations, especially calcium and magnesium, becomes too high, the sodium tends to replace the calcium and magnesium ions on clay particles. The predominance of sodium ions on clay particles has the effect of dispersing the soil particles and decreasing the soil permeability. To determine the sodium hazard, the Sodium Adsorption Ratio (SAR) has been developed. It is defined as follows:

$$SAR = \frac{Na}{\left[(Ca + Mg)/2\right]^{0.5}} \tag{8.1}$$

Where Na, Ca, and Mg are concentrations of the respective ions in milli equivalents per liter of water (meq/L).

In chemistry, an equivalent weight of an ion is equal to its molecular weight divided by absolute value of ion charge. For example the equivalent weight of calcium is 40/2 or 20 g equivalent.

When industrial wastes are included in the wastewater to be irrigated, adjustment of the pH and SAR may be needed. The wastewater to be applied should have a pH within the range of 6.0 to 9.5 to avoid adverse effects to site vegetation. Wastewaters with high SAR must be pre-treated to remove Na or accompanied by special soil management procedures to compensate for the effect of the sodium. The SAR of wastewaters used for irrigation should be no more than 8 to 10; otherwise these wastewaters should not be used in irrigation.

Some pre-application methods that may be used to control the chemical reactions in the soil could include:

- Pre-treatment controls, such as industrial source control or chemical precipitation, if the amount of potentially toxic elements and chemicals in the wastewater are likely to exceed the chemical removal mechanisms in the soil.
- Adjustment of wastewater pH and SAR to acceptable levels.

The relationship of potential problems to concentrations of major inorganic constituents in irrigation waters is shown in Table 8.6.

8.3.3 Biological removal mechanisms

The biological transformations that occur in the soil include organic matter decomposition and nutrient assimilation by plants. These transformations occur in the biologically active upper few centimeters of the soil, i.e., the rooting zone. The numbers of bacteria are large ranging from one to three billions per g of soil. The great diversity of native organisms enhances the capability of a soil to degrade the variety of natural and man-made organic compounds in the applied wastewater.

The presence or absence of oxygen in the soil has a significant effect on the rate and end products of degradation. The oxygen status of the soil is a function of soil porosity. Soil properties that allow for rapid infiltration and transmission of the applied wastewater also yield good oxygen movement; low and intermittent wastewater application rates used with SR system normally result in aerobic conditions, rapid organic matter decomposition, and oxidized end products.

Table 8.6 Relationship of potential problems to concentration of major inorganic constituents in irrigation waters for arid and semi-arid climates (Ayers and Westcot 1976)

Problem and related constituent	No problem	Increasing problem	Severe problem
Salinity[a]			
EC of irrigation water, mmhos/cm	<0.75	0.75-3.0	>3.0
Permeability			
EC of irrigation water, mhos/cm	>0.5	<0.5	<0.2
SAR (sodium adsorption ratio)[b]	<6.0	6.0-9.0	>9.0
Specific ion toxicity[c]			
From root absorption			
Sodium (evaluated by SAR)	<3	3.0-9.0	>9.0
Chloride, meq/L	<4	4.0 – 10	>10 >355
Chloride, mg/L	<142	142-355	2.0-10.0
Boron, mg/L	<0.5	0.5-2.0	
From foliar absorption (sprinklers)[d]			
Sodium, meq/L	<3.0	>3.0	-
Sodium, mg/L	<69	>69	-
Chloride, meq/L	<3.0	>3.0 >106	-
Chloride, mg/L	<106		-
Miscellaneous[e]			
HCO_3^-, meq/L	<1.5	1.5-8.5	>8.5
HCO_3^-, mg/L	<90	90-250	>520
pH		Normal range = 6.5-8.5	

Note: Interpretations are based on possible effects of constituents on crops and/or soils. Suggested values are flexible and should be modified when warranted by local experience or special conditions of crop, soil, and method of irrigation.

[a] Assuming water for crop plus water needed for leaching requirement will be applied. Crops vary in tolerance to salinity. Electrical conductivity (EC) mmhos/cm x 640 = approximate total dissolved solids (TDS) in mg/L or ppm.

[b]
$$SAR = \frac{Na}{[(Ca + Mg)/2]^{0.5}}$$

where Na = sodium; Ca = calcium; Mg = magnesium, in all meq/L.

[c] Most tree crops and woody ornamentals are sensitive to sodium and chloride (use values shown). Most annual crops are not sensitive.

[d] Leaf areas wet by sprinklers (rotating heads) may show a leaf burn due to sodium or chloride absorption under low-humidity, high-evaporation conditions. (Evaporation increases ion concentration in water films on leaves between rotations of sprinkler heads.)

[e] HCO_3^- with overhead sprinkler irrigation may cause a white carbonate deposit to form on fruit and leaves.

Oxygen at the soil surface must diffuse into the soil layer or waste-soil matrix, depending on the nature of the wastewater application and soil-water migration of liquid and waste organics (Figure 8.7). The transfer mechanism is oxygen diffusion. Because soil pores are usually smaller and having solids deposits, the diffusion of oxygen into soils may be the rate limiting step in satisfying the waste oxygen demand and maintaining aerobic soil conditions. The phenomena of transfer of photosynthetic oxygen from the crop's leaves to the root zone, similar to that of aquatic weeds (see Chapter 7), is not yet well understood.

As a result of organic matter decomposition, elements such as nitrogen, phosphorus, and sulfur are converted from organic to inorganic forms. Many of these mineralized constituents can be assimilated by plants. Crops are an essential part of the SR and OF processes (see Table 8.2).

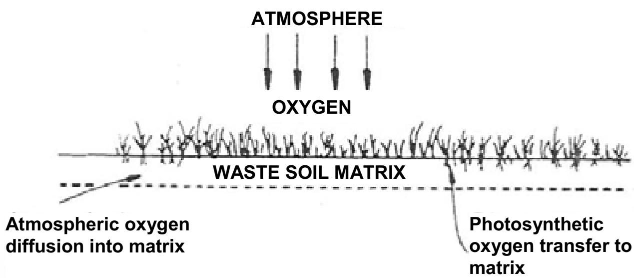


Figure 8.7 Schematic of oxygen transfer to stabilize organic compounds applied to land

The biological nitrification processes in the soil produce nitrate from ammonia and organic nitrogen under aerobic conditions. However, nitrate compounds can be reduced into nitrogen gas under anoxic conditions as a result of denitrification.

It is possible to consider both gaseous nitrogen losses (volatilization and denitrification) and nitrogen removal by plant uptake as control mechanisms for the nitrogen in the applied wastewater.

Crop selection and management are important components of the wastewater irrigation system. Plant uptake of nitrogen is in the range of 100 to 400 kg per ha per growing season, depending upon specific crop and management techniques. Data on nutrient (N, P, K) uptake rates for selected crops are given in Table 8.7. It appears from this table that forage crops have ability to uptake nutrients better than field crops.

Table 8.7 Nutrient uptake rates for selected crops, kg/(ha-yr) (adapted from U.S. EPA 1981 and local agricultural offices of Asian countries)[a]

	Nitrogen	Phosphorus	Potassium
Forage crops			
Alfalfa[a]	225-540 130-	22-35	175-225
Bromegrass	225 400-675	40-55	245
Coastal bermudagrass	200-270	35-45	225
Kentucy bluegrass	235-280 335-	45	200
Quackgrass	450	30-45	275
Reed Carnarygrass	200-280	40-45	315
Rye grass	175	60-85	270-325
Sweet clover[a]	150 – 325	20	100
Tall fescue	250 – 350	30	300
Orchargrass		20 – 50	225 – 315
Field crops			
Barley	125	15	20
Corn	175 – 200	20 – 30	110
Cotton	75 – 110	15	40
Grain sorghum	135	15	70
Potatoes	230	20	245 – 325
Soya beans	250	10 – 20	30 – 55
Wheat	160	15	20 - 45
Rice			
Non sensitive to light	110	40	40
Sensitive to light	60	40	40
Mustard	60	40	20
Cabbage	210 – 240	35 – 40	300 – 345
Carrot	180 – 190	20 – 30	325 – 445
Onion	120 – 170	20 – 30	120 – 140
Tea	120	45	N.A.
Orange	330	240	250
Coffee	110	20	125

[a] Legumes will also take nitrogen from the atmosphere. These are data for temperate climates where the growing season is usually once a year. For tropical areas where there are more than one growing season in a year, the unit of nutrient uptake rates can be changed to kg/(ha-growing season)

N.A. = not available

The nitrogen application rate should be determined from a nitrogen balance on the system. The important processes involved in nitrogen removal from wastewater applied to the land are ammonia volatilization, crop uptake and removal, soil adsorption of ammonia, incorporation into the soil organic fraction, and denitrification. With the slow rate process, nitrogen management is principally due to crop uptake with some denitrification. The proper application rate will be that which, when crop uptake and denitrification are considered, maintains the nitrogen concentration in the percolating water below allowable limits, generally less than 10 mg/L nitrate nitrogen or 45 mg/L nitrate to prevent methamoglobenemia, a disease caused by drinking water that contains too high nitrate concentrations.

The factors that favor denitrification in the soil are: high organic matter, fine textured soil, frequent wetting or high groundwater table, neutral to slightly alkaline pH, vegetative cover, and warm temperature.

Denitrification losses of nitrogen can range up to 50% depending upon how the land disposal site is managed. A conservative estimate would be to assume denitrification and volatilization losses to be 20 to 30% of the applied nitrogen. Consideration of plant uptake and these losses as the nitrogen control mechanisms will reduce the risk of excessive nitrogen in the percolate (Broadbent *et al.* 1977) as shown in example 8.2.

Pre-application approaches related to biological mechanisms could include nitrogen removal prior to land application where the nitrogen application rate is the limiting factor and the required land area is excessive. Such removal could include nitrification followed by denitrification in preliminary wastewater storage ponds.

8.4 SYSTEM DESIGN AND OPERATION

Three methods can be used to determine wastewater application rates in land treatment systems: field measurements; comparison with application rates from similar existing projects; and combination of the above two methods together with previous experience and judgement. In view of the present state of the art in land treatment technology, the third method is recommended, so as to maximise the land treatment efficiency and minimise operation and maintenance costs.

In SR or irrigation systems, application rates are determined by using the water balance, the nitrogen balance, and measured or estimated percolation rates. In rapid infiltration systems, field measurements are necessary, coupled with a detailed knowledge of the subsurface hydrology and comparisons with existing systems. In overland flow systems, application rates depend mostly on required wastewater treatment and are currently determined by comparison with existing treatment systems or by calculation from kinetic equations.

8.4.1 Irrigation or SR system

Wastewater application rate

Typical wastewater application rates for irrigation or slow rate systems range from about 1.5 to 10 cm/week (Figure 8.1 and Table 8.2). The choice depends on the climate, soil permeability, crop type and management practices, and required quality of the treated water. Information on climate and soil permeability can be obtained from meteorological data and site investigation, respectively; this information is used in the water balance calculation as shown in the next section on "Hydraulic loading rate". The required quality of the treated water is usually evaluated by using the nitrogen balance. When crop production is the priority, the irrigation requirements of the crop may limit the application rate.

Example 8.1

For a clay-loam soil, which is irrigated periodically, the moisture content before irrigation is 19% by weight. If the effective infiltrated irrigation water is 1,000 m^3 per hectare, estimate the soil moisture content after irrigation. Assume that the soil's bulk density is 1.35, and the depth to which the soil is wetted is 90 cm. What should be the period of irrigation if the evapotranspiration rate is 250 mm/month?

Infiltrated water, I = 1,000 m^3/10,000 m^2 = 100 mm

The effect of irrigation on the soil moisture content can be estimated from the following equation.

$$I = (P'' - P')\, S.D/100 \tag{8.2}$$

Where,

I = effective infiltrated irrigated water, mm
P'' = final moisture content, % by wt.
P' = initial moisture content, % by wt.
S = soil's bulk density
D = depth of soil to the root zone to be wetted, mm

Hence,

100 mm = (P'' - 19%) 1.35 x 900/100

Thus, P'' = 27.3%

Therefore, soil moisture content after irrigation = 27.3%

$$\text{Required irrigation period} = \frac{100 \text{ mm}}{250 \text{ mm/month}} = 12 \text{ days}$$

Select 5 days for irrigation period and 7 days for resting or drying period. Wastewater application rate is 100 mm/5 days or 20 mm/day during the irrigation period.

Hydraulic loading rate

In the water balance, the inputs are wastewater application and precipitation and the outputs are evapotranspiration, percolation and runoff. The precipitation and evapotranspiration values should be determined for a design year that is wetter than the normal climatic condition. The percolation rate can be either estimated from the soil permeability or measured in the field. Recommended field measurement techniques for soil percolation rates are basin flooding or the sprinkler infiltrometer, the details of which can be found in U.S. EPA (1981) or other handbooks on groundwater and hydrology.

Using water balance, the following is obtained:

$$L_h + P_p = ET + W + R \tag{8.3}$$

Where:

L_h = wastewater hydraulic loading rate, cm/year
P_p = design precipitation, cm/year
ET = evapotranspiration, cm/year
W = percolation, cm/year
R = net runoff, cm/year

For slow rate systems, the design is such that there is no surface runoff. Therefore net runoff, R, is usually negligible in the calculation.

Nitrogen loading rate

Because of the ability of nitrate nitrogen to move with the percolating water, nitrogen is often the limiting water quality parameter in SR and RI systems. In slow rate systems, the input nitrogen is balanced against crop uptake, denitrification, and the nitrogen that percolates through the root zone. The climate can also influence the nitrogen balance. For example, in a humid climate, the water from precipitation (in excess of evapotranspiration) can dilute the percolating nitrogen concentration, as shown in Example 8.2 and Table 8.8 for a percolate containing a maximum of 10 mg/L nitrogen. Thus, under a humid climate condition (as shown in Table 8.8), 36% more nitrogen can be applied than in the arid climate.

The annual nitrogen balance is given by:

$$L'_h = U + D + 0.1\ W\ C_n \tag{8.4}$$

Where,

L'_h = wastewater nitrogen loading, kg/(ha-yr)
U = crop nitrogen uptake, kg/(ha-yr)
W = percolation rate, cm/yr
C_n = percolate nitrogen concentration, mg/L
D = denitrification rate, kg/(ha-yr)

The term 0.1 WC_n on the right side of Equation 8.4 is the percolate N loading or P'_n whose unit is kg/(ha-yr).

Table 8.8 Comparison of nitrogen loadings in humid and arid climates (Olsen and Kemper 1968)

Parameter	Humid climate	Arid climate
Applied nitrogen, mg/L	25	25
Precipitation minus evapotranspiration, m/yr	0.5	-0.5
Crop uptake, kg/ha	336	336
Denitrification, % of applied N	20	20
Hydraulic loading, m/yr	4.0	2.9
Wastewater nitrogen loading, kg/ha-yr	980	720

Example 8.2

Determine the nitrogen balance for a designed percolate nitrogen concentration (C_n) of 10 mg/L for the following conditions.

	Humid	Arid
1. Applied N concentration, C'_n, mg/L	25	25
2. Crop nitrogen uptake, U, kg/(ha-yr)	336	336
3. Denitrification, as % of applied N	20	20
4. Precipitation (P_p) – Evapo-transpiration (ET), cm/yr	50	-50

Assuming denitrification (D) is 20% of the wastewater nitrogen loading (L'_n) From Equation 8.3, the annual water balance is:

$$L_h + P_p = ET + W + R$$

or $$W = L_h + P_p - ET - O \text{ (assuming R is negligible)}$$

$W = L_h + 50$ (humid)
$W = L_h - 50$ (arid)

The amount of percolating water, W, resulting from the applied wastewater, L_h, has a significant effect on the allowable nitrogen loading, L'_n.

From Equation 8.4, the annual N balance is:

$$L'_n = U + D + 0.1\ W\ C_n$$
$$\text{for humid } L'_n = 336 + .2\ L'_n + (0.1)(L_h + 50)\ 10$$
$$\text{for arid } L'_n = 336 + .2\ L'_n + (0.1)(L_h - 50)\ 10$$

The relationship between the nitrogen loading and the hydraulic loading is : $L'_n = 0.1\ C'_n\ L_h$ (SI units). Where, L'_n = wastewater nitrogen loading, kg/(ha-yr); C'_n = applied nitrogen concentration, mg/L; L_h = wastewater hydraulic loading, cm/yr.

$$L'_n = 0.1 \times 25\ L_h = 2.5\ L_h$$
or
$$L_h = 0.4\ L'_n$$

For humid climate,

$$L'_n = 336 + .2\ L'_n + 0.1(0.4L'_n + 50)\text{x}10$$
$$= 965 \text{ kg/(ha-yr)}$$
$$L_h = 965 \times 0.4 = 386 \text{ cm/yr}$$

For arid climate,

$$L'_n = 336 + .2L'_n + 0.1(0.4L'_n - 50)\text{x}10$$
$$= 715 \text{ kg/(ha-yr)}$$
$$L_h = 715 \times 0.4 = 286 \text{ cm/yr}$$

Summary of solutions

	Humid	Arid
1. Wastewater N loading, (L'_n), kg/(ha-yr)	965	715
2. Wastewater hydraulic loading, (L_h), cm/yr	386	286
3. Percolating water, (W), cm/yr	436	236
4. De-nitrification, (D), kg/(ha-yr)	193	143
5. Percolate N loading (P'_n), kg/(ha-yr) ($P'_n = 0.1\ C_n\ W = L'_n - U - D$)	436	236

Application schedule

The application schedule for irrigation depends on the soil permeability, type of crop, application technique, and the climate. Operator convenience should also be considered. For permeable soils, the schedule should be to irrigate once a week or more frequently. For less permeable soils using surface irrigation, the application schedule should include a longer period of drying.

8.4.2 Rapid infiltration or RI system

Wastewater application rate

In rapid infiltration, evaporation and vegetation are relatively unimportant, but the soil permeability is critical. It is therefore important to concentrate the planning and design on determining the optimal infiltration rate to ensure that the system will work hydraulically while providing the necessary wastewater treatment. As given in Figure 8.1 and Table 8.2, typical application rates for RI systems range from 10 to 250 cm/wk.

Hydraulic loading rate

Although the soil permeability can be related to the infiltration rate, as previously described, it is recommended that the soil profile be evaluated and that field measurements of infiltration rates be conducted. The preferred method of determining the infiltration rate depends on the nature of the soil profile. If the profile is generally homogeneous, a surface flooding basin 2 m or more in diameter can be used. The basin is filled with clean water until the soil is saturated, and then the rate of infiltration is measured. Clean water is generally used unless the actual wastewater is available.

Treatment performance

In rapid infiltration systems, the required treatment performance is of primary importance in determining the application rate. Lance and Gerba (1977) showed that decreasing the application rate from the hydraulic limit could result in increased removals of constituents, especially nitrogen. Because the chief mechanism of nitrogen removal in rapid infiltration systems is denitrification, the following requirements of biological denitrification must be met: adequate detention time, anoxic conditions (or at least anaerobic micro-sites), and adequate carbon to drive the reaction. The reduction in application rate increases detention time and increases the potential for denitrification. The effect of infiltration rate on N removal for a rapid infiltration site in Phoenix, Arizona, is shown in Figure 8.8.

Application schedule

Treatment efficiency in rapid infiltration systems responds to variations in application cycle. Short and frequent application schedules such as 0.5 to 3 days on and 1 to 5 days drying, maximize nitrification probably because the soil is exposed more to air and aerobic conditions, but minimize denitrification or nitrogen removal. As the drying time during the cycle increases, the potential for nitrogen removal increases. For example, the application schedule at Hollister, California, is 1 to 2 days on and 14 to 21 days off. At Phoenix, Arizona, maximum nitrogen removal occurred when 10 days on was followed by 10 to 20 days off.

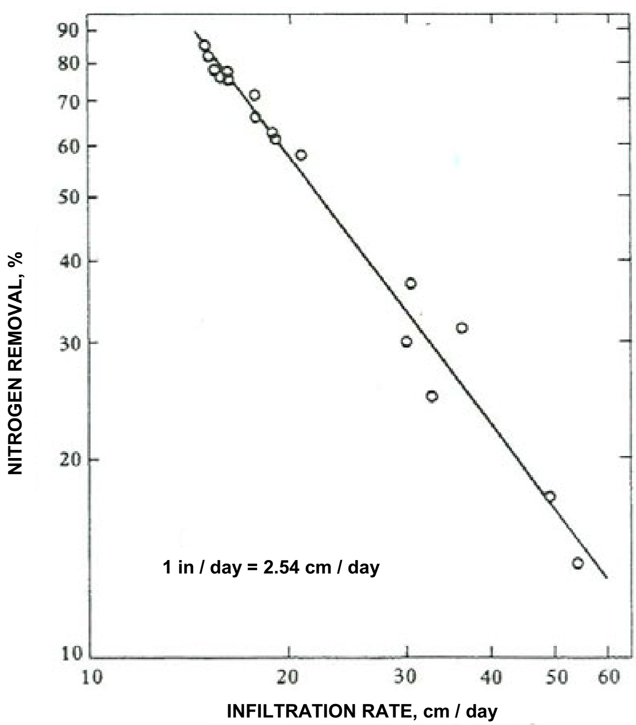


Figure 8.8 Effect of infiltration rate on nitrogen removal for rapid infiltration, Phoenix, Arizona (From Lance and Gerba 1977; reproduced by the permission of Pergamon Books Ltd)

Example 8.3

A sandy soil with an infiltration capacity of 90 cm/day will be used for wastewater treatment and renovation through the rapid infiltration (RF) process. Based on a laboratory study and Figure 8.1, the following wastewater application modes were found suitable for the RI operation.

Average wastewater application rate	= 30 m/yr
Application period	= 4 days
Resting period	= 10 days

Determine whether this RI operation will create flooding condition or not.

Wastewater cycle time	= 4 +10	= 14 days
Number of cycle per year	= 365/ 14	= 26
Wastewater application per cycle	= 30/26	= 1.15 m/cycle

Wastewater application rate	= (1.15 m/cycle)/ 4 days
	= 0.29 m/day-cycle
	= 29 cm/day-cycle

The wastewater application of 29 cm/day is less than the soil infiltration capacity of 90 cm/day, so flooding will not occur.

Note: Suppose 1 ha land is used for this RI unit, the wastewater flow would be 822 m^3/day. Since the wastewater application rate of 29 cm/day is equivalent to a wastewater flow rate of 2,900 m^3/day, for the application period of 4 days, a storage reservoir of 11,600m^3 capacity should be built to store the wastewater sufficient for the above RI operation.

8.4.3 Overland flow or OF system

Wastewater application rate

Overland flow is a form of a fixed-film biological reactor. The application rate should therefore be predictable on the basis of the kinetics of treatment and the required treatment levels. For example, high-quality effluent has been produced in research projects using these application rates: raw wastewater, 10 cm/week; primary effluent, 15 to 20 cm/week; and secondary effluent, 25 to 40 cm/week. With all three application rates, the runoff contained less than 10 mg/L BOD_5 on the average. Slopes of the land were 2 to 4% and 36 m long (Tucker and Vivado 1980).

Wastewater application rates for OF systems are usually determined from comparisons with existing systems and research projects (see also Figure 8.1 and Table 8.2). For raw wastewater, 7.5 to 10 cm/week should be considered. For primary effluent, 10 to 20 cm/week could be used, depending on the level of overall treatment required. For secondary effluent, either from waste stabilization ponds or conventional secondary treatment facilities (e.g. activated sludge or trickling filters), the need is either for polishing (further reductions for BOD_5 and suspended solids) or for nutrient removal. For polishing, 20 to 40 cm/week could be considered. For nutrient removal, only 10 to 20 cm/week may be possible because adequate detention time is necessary for denitrification.

Application schedule

Experience with existing systems suggests application schedules to be 6 to 8 hours on and 16 to 18 hours off over 5 to 6 days/week. At Melbourne, Australia, however, the application has been continuous rather than intermittent. The optimum cycle will depend on the climate and the BOD_5 loading. Other considerations include the harvesting of grass and the potential for propagation of insects.

8.4.4 Other design considerations

There are many factors that determine the area required for a wastewater land treatment system. These factors are related to the characteristics of the soil, wastewater, climate, crop, pre-application treatment, and should be evaluated using site-specific information.

In determining the required land area, the land area for each potentially limiting parameter (such as hydraulic, nitrogen, toxic compounds and salt loadings) should be evaluated. The parameter that requires the largest land area to avoid environmental problems becomes the limiting parameter. When the land area determined for the limiting parameter is used for the design of a land treatment system, there is an additional degree of safety in terms of the application rates of the other constituents or parameters of concern.

It should be possible to determine application rates for land treatment systems on a case-by-case basis using data on soil infiltration rates, climate, wastewater characteristics, and required treatment performance. Unfortunately, neither the relationship between the infiltration rate and loading rate nor the relationship between the loading rate and treatment performance have been developed to the point where they can be used in design without requiring comparisons with other land treatment systems.

Pre-application treatment

Pre-application treatment of wastewater to be used for land treatment is necessary to:

- Inactivate the entero-pathogenic organisms to an acceptable levels so that public health risks to the workers, grazing animals or human beings who consume those irrigated crops are minimized (see section 8.7),
- Minimize operational problems in distribution systems such as clogging of the spray nozzles and distribution pipes, etc.,
- Lengthen the working life of land treatment sites as clogging of the soil pores will be less when pre-treated wastewater is applied,
- Prevent nuisance conditions during wastewater storage prior to being applied to land.

Screening, screening with comminution, aeration, ponding, and disinfection are the common types of pre-treatment facilities used. In case of industrial wastewaters containing some toxic compounds, other pre-application treatment such as chemical precipitation and flocculation/sedimentation might be necessary. Where concern is on nitrate contamination to groundwater aquifers, pre-application treatment may include ammonia stripping, water hyacinth pond treatment, or storage ponds having a long detention time, to reduce the nitrogen content.

The level of pre-application treatment provided should be the minimum necessary to achieve objectives stated above. Any additional treatment will, in most cases, only increase cost and energy use.

Crop selection

Crop selection is an important factor in SR and OF processes. Presence of suitable crops on the application area will reduce the erosion, provide support media for microorganisms, remove the wastewater nutrients by plant uptake and produce revenue where markets for these crops exist. Nutrient uptake capacity (see Table 8.7), tolerance to high soil moisture conditions, consumptive use of water and irrigation requirements and revenue potential should be considered when selecting a crop for SR and OF systems. In SR system, presence of crop will maintain or increase the soil infiltration rate. In OF system, a mixture of grasses is generally preferred over a single species. Corn and paddy are also suitable crops to be used but the public health aspects should be studied in detail as the public consumes these crops.

Storage

Storage of wastewater is required for any process of land treatment in order to equalize the incoming flows, to maintain constant application rates, and in the case of repairs or operational problem in the distribution system. Even though SR and RI systems are capable of operating during adverse climatic conditions storage may be required. In the case of OF system, storage is necessary to accommodate the wastewater during rainy and winter seasons due to reduced hydraulic loading or complete shut down, and also to accommodate stormwater runoff. Generally 5-10 days of storage is sufficient to overcome the problems.

Distribution system

Distribution system design consists of two important components:

- selection of the type of distribution system, and
- detail design of system components.

Method of wastewater distribution varies with the type of land treatment system. For SR system, either surface distribution system in which wastewater is applied to the land at one end and allowed to spread over the field by gravity (Figure 8.2 b) or sprinkler distribution system where the wastewater is spread over the land by sprinklers (Figure 8.2 c) is suitable. In the case of RI system, wastewater distribution is usually by surface spreading (Figure 8.3). This method employs gravity flow from piping systems or ditches to flood the application area. Wastewater distribution onto OF slopes can be achieved by surface methods, low-pressure sprays and high-pressure impact sprinklers. Choice of the appropriate system should be based on minimization of operational difficulties such as uneven distribution onto the slope, and also the operational cost of the system. If surface distribution method is adopted, the land should be perfectly levelled to avoid ponding. Extreme care should be taken when sprinkler system is used for the treatment area situated near residential areas to avoid spreading of pathogens due to aerosols and wind action.

8.5 LAND TREATMENT- DESIGN EQUATIONS

Mathematical models for the three land treatment processes have not been extensively developed. This is due partly to the complex nature of land treatment involving the physical, chemical and biological reactions. Efficiency of a land treatment system also depends on climate and soil conditions at the specific site. SR process is normally designed based on practical experiences. Some empirical and rational models for the RI and OF processes have been developed.

8.5.1 RI process

Treatment performance of RI systems with respect to nitrogen and phosphorus removal is given below.

Nitrogen removal

Application rates up to 30 cm/day with 20 mg/L of ammonia will result in a nitrified effluent. As wastewater temperatures drop, the rate of nitrification will also decrease. For nitrification, the loading cycle should consist of short application periods (1 day or so) and relatively long drying periods (5 to 10 days) to allow for aeration and the occurrence of aerobic conditions in the soil favourable for the growth of nitrifying bacteria.

Nitrogen removal by denitrification requires both adequate organic carbon and adequate detention time. Nitrogen removal can be expressed by the following equation (Reed and Crites 1984).

$$N_t = \frac{TOC - 5}{2} \tag{8.5}$$

Where:

N_t = total nitrogen removal, mg/L
TOC = total organic carbon in the applied wastewater, mg/L

The 5 mg/L of residual TOC is typical for municipal wastewater passage through about 5 ft (1.5 m) of soil. The coefficient 2 in the denominator is based on experimental data where 2 g wastewater carbon was required to denitrify 1 g of wastewater nitrogen.

Nitrogen removal is also related to infiltration rate and an application rate of 15 cm/day is recommended as a maximum where 80% N removal is needed with secondary effluent (Figure 8.8). When primary effluent is used, the maximum application rate is recommended not to exceed 20 cm/day.

Phosphorus removal

There is no crop uptake in RI systems and the nature of the soils and high hydraulic rates used require greater travel distances in the soil for effective P removal.

An equation to predict phosphorus removal at RI sites has been developed from data collected at number of operating systems (Reed and Crites 1984).

$$P_x = P_o .\exp(-kt) \tag{8.6}$$

Where:

P_x = total P concentration at a distance x along the percolate flow path, mg/L
P_0 = total P concentration in the applied wastewater, mg/L
k = instantaneous rate constant, 0.002/hr at neutral pH
t = detention time = x.θ/I, hr
x = distance along the flow path, in
θ = volumetric water content, usually 0.4
I = infiltration rate, in/hr

8.5.2 OF process

Based on a pilot study conducted by Smith and Schroeder (1985), it was found that the removal of organic material from primary effluent is accomplished in two stages as a function of slope length (z) and application rate (q).

In the first stage a rapid removal of organic matter takes place within the first 6 to 10 meters of slope length and in the second stage a slower rate of organic removal takes place in the remainder of the slope.

From a practical design and operation standpoint only the second stage would be the basis for design and operation.

The probable reason for the observation of the two distinct rates of organic removal over the length of the overland flow slope is that settleable matter is removed readily by sedimentation in the first few meters, leaving colloidal and soluble organic material to be removed at a slower rate by adsorption and, ultimately, bacterial assimilation over the remaining length of the slope.

The mathematical model was developed from the studies made on lands with down-slope grade of 2% and cross-slope grade of 0.2% with a mixture of perennial rye grass, annal rye grass, orchard grass, and tall fescue grass. The tall fescue grass was predominant.

BOD_5 and TOC removal

Removal of BOD_5 and TOC from wastewater and primary effluent after the first 9 m of travel down the overland flow slope followed the first-order removal model:

$$C_z/C_o = A.\exp(-K.z) \tag{8.7}$$

Where:

z = distance down-slope, in m (z > 9 m)

C_z = organic concentration (BOD_5 or TOC) at a distance (z) down-slope, mg/L

C_o = initial organic concentration (BOD_5 or TOC), mg/L

K = empirically determined overall rate constant

A = empirically determined coefficient

It has been shown that BOD_5 concentrations in the runoff from overland flow slopes approach a nonzero value in the range of 3 to 5 mg/L. Effluent BOD_5 and TOC concentrations approach average values of 5 mg/L and 7 mg/L, respectively, after 64 m of down-slope travel. Hence the removal models were modified to account for this as follows:

BOD_5 removal model:

$$(C - 5)/C_o = A.\exp(-K.z) \tag{8.8}$$

TOC removal model:

$$(C - 7)/C_o = A'.\exp(-K'.z) \tag{8.9}$$

Where:

C = required effluent BOD_5 or TOC concentrations at distance z

K and K' = empirical rate constants for BOD_5 and TOC removal, respectively

A and A' = empirical coefficients for BOD_5 and TOC removal, respectively

The overall rate constants K and K' in Equations 8.8 and 8.9 vary as a function of application rate q, according to the following equation:

$$K \text{ or } K' = k/q^n \tag{8.10}$$

Where, k and n are empirical coefficients and q is wastewater application rate whose unit is m^3/(hr-m of slope width).

Then,

BOD_5 model: $(C - 5)/C_o = A.\exp(-k.z/q^n)$ (8.11)

TOC model : $(C - 7)/C_o = A'.\exp(-k'.z/q^n)$ (8.12)

The values of coefficients k and n, obtained for q values ranging from 0.1 - 0.37 m^3 / (hr-m) are summarized in Table 8.9.

A family of curves that describe BOD_5 and TOC removal as functions of slope length (up to 64 m) and application rates (0.1, 0.16, 0.25, and 0.37 m^3/(hr-m)) for raw wastewaters and primary effluent are shown in Figures 8.9 – 8.12 (application periods were up to 16 hr/day). Either application rate or slope length may be used as the independent design variable. The variation of A and A' with q was found to be inconsistent. Therefore, for design purposes, it would be satisfactory to use directly the family of curves given in Figures 8.9 to 8.12.

When designing a system, the required or desired level of treatment is known. Thus a value for $(C - c)/C_o$, according to Equation 8.8 or Equation 8.9 can be established. If slope length is used as the independent variable then a design value for slope length, z, is selected. The required value of application rate, q, is then determined by entering the appropriate curve with the known values of z and $(C - c)/C_o$. Alternatively, if application rate q is the independent design variable, then a value for q is selected and the required value of slope length, z is taken from the curves. The independent design parameter used depends on the individual case.

Table 8.9 Summary of coefficients for BOD_5 and TOC removal models (Smith and Schroeder 1985)

	Coefficient value	
Applied wastewater	k	N
Primary effluent		
BOD_5	0.043	0.136
TOC	0.038	0.170
Screened raw wastewater		
BOD_5	0.030	0.402
TOC	0.032	0.350

From Smith and Schroeder (1985); reproduced by the permission of the Water Pollution Control Federation, U.S.A.

A later study by Witherow and Bledsoe (1986) confirmed the removal of BOD_5, TOC, total suspended solids (TSS) and NH_4-N to follow the models given in Equation 8.11 and 8.12. By setting n at 0.5 and using field data from a 4-ha OF site in Oklahoma, U.S.A., the intercept constant A and rate constant k of equation 8.13 for the four pollutants are given in Table 8.10.

$$C_z/C_o = A.\exp(-k.z/q^{0.5}) \tag{8.13}$$

The total area required for slopes must be determined to complete the system design. Total area required may be computed by the following equation:

$$\text{Area} = (Q)(z)/(q)(p_d) \tag{8.14}$$

Where,

Area = total area of OF site, m^2
Q = design daily flow, m^3/day
z = slope length, m
q = application rate, m^3/(hr-m)
P_d = daily application period, hr/day

Design values for Q, p and q should be selected to allow operating flexibility during periods when parts of the system must be shut down for harvesting or repairing.

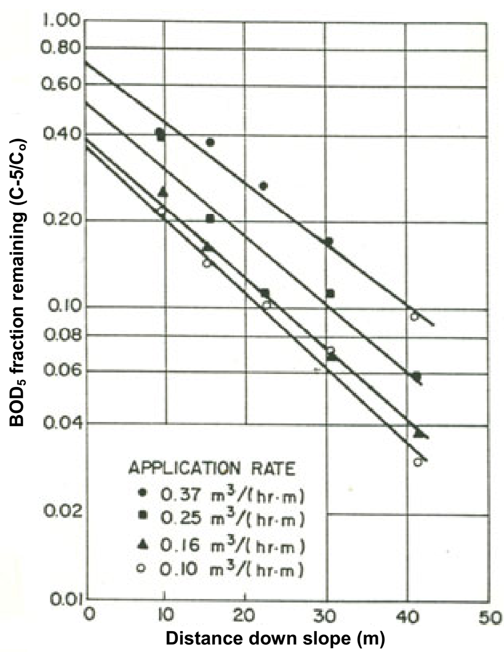


Figure 8.9 BOD_5 fraction remaining versus distance down-slope; application rate study with screened raw wastewater (Smith and Schroeder 1985)

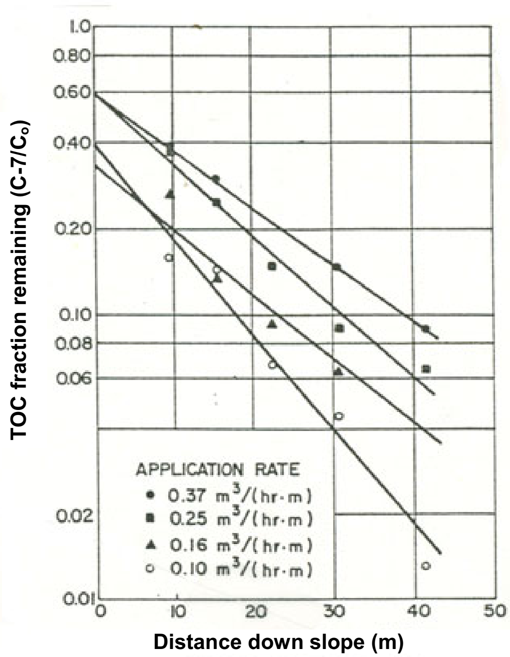


Figure 8.10 TOC fraction remaining versus distance down-slope; application rate study with screened raw wastewater (Smith and Schroeder 1985)

Table 8.10 Intercepts (A) and rate constants (k) of Equation 8.13 (adapted from Witherow and Bledsoe 1986)

Pollutants	A	k (m/hr)
TSS	0.44-0.96	0.024-0.056
BOD_5	0.58-0.88	0.030-0.046
TOC	0.57-0.88	0.016-0.039
NH_4-N	0.99-1.12	0.016-0.054

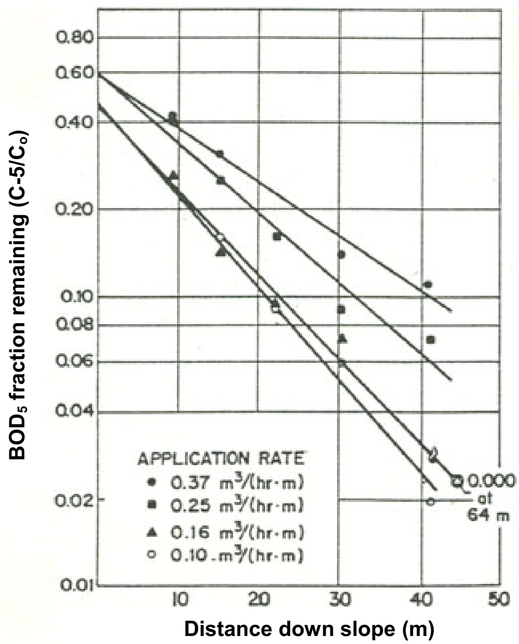


Figure 8.11 BOD_5 fraction remaining versus distance down-slope; application rate study with primary effluent (Smith and Schroeder 1985)

Design daily flow (Q)

It is preferable to provide equalization or off-line storage facilities to allow for constant application rates and short-term storage during power outage or extremely heavy precipitation. The design daily flow should be based on peak seasonal average daily flow. For systems without such storage facilities the design daily flow Q should be based on the average flow during selected period depending on the flow conditions.

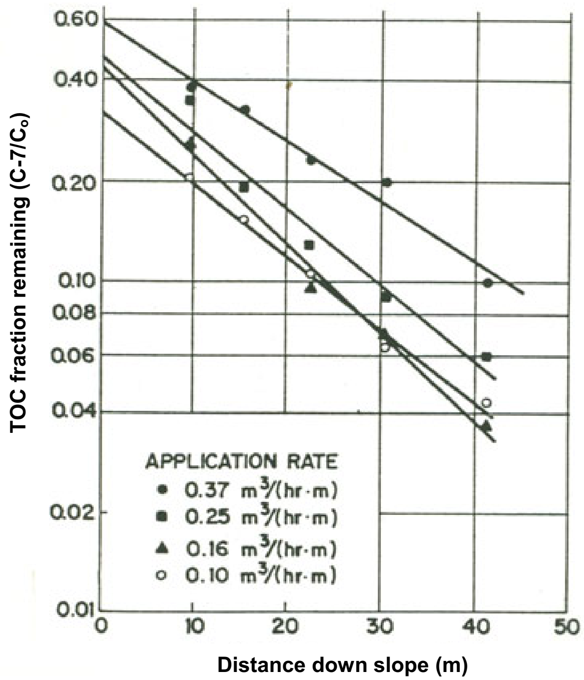


Figure 8.12 TOC fraction remaining versus distance down-slope; application rate study with primary effluent (from Smith and Schroeder 1985; reproduced by permission of the Water Pollution Control Federation, USA)

Design application rate (q)

The design q value for an OF should generally match with the infiltration rate of the soil or vegetated surface of the soil, to prevent excessive run-off and impairment of effluent quality. The value of q in Equation 8.14 should be less than the value used to determine z to provide a safety factor in process performance and to allow operating flexibility by permitting a range of application rates to be used. A factor of 1.5 is suggested for design. Thus, if a design value for q of 0.37 m^3/(hr-m) is used to determine z, then a design value for q of 0.25 m^3/(hr-m) should be used in Equation 8.13 to calculate the required area.

Design application period (P_d)

Design application periods of 8-12 hr/day are recommended. For small systems it may be more convenient or cost-effective to operate only during one working shift. In this case, the entire area would receive the design daily flow during 8-hour application period. Storage facilities would be required to hold wastewater during the 16 hr non-operating period.

Example 8.4

Determine the area required for land treatment of wastewater using the overland flow method.

The following information is given: screened raw wastewater is to be used; the flow (Q) is 3,000 m^3/day; the influent BOD_5 (C_o) is 200 mg/L; and the required effluent BOD_5 (C) is 20 mg/L.

The necessary design calculations are as follows:

Compute the required removal ratio, $(C - 5)/C_o$, from Equation 8.8:

$$(C - 5)/C_o = (20 - 5)/200 = 0.07$$

Select an application rate, q, in valid range of the model:

$$q = 0.25 \text{ m}^3/\text{(hr-m)}$$

Determine required value of slope length, z, using Figure 8.9:

$$z = 37 \text{ m}$$

Select application period, P_d.

$$P_d = 8 \text{ hr/day}$$

Compute q for area calculation

$$q = (0.25 \text{ m}^3/\text{(hr-m)}/1.5$$
$$q = 0.17 \text{ m}^3/\text{(hr-m)}$$

Compute required total area from Equation 8.14. Assume 7 days/wk application frequency.

$$\text{Area} = (Q)(z)/(q)(P_d)$$
$$\text{Area} = (3{,}000 \text{ m}^3/\text{day})(37 \text{ m})/(0.17 \text{ m}^3/\text{(hr-m)})(8 \text{ hr/day})$$
$$= 81{,}620 \text{ m}^2 \approx 8.2 \text{ ha}$$

Comparison of current design based on hydraulic loading

Assume the hydraulic loading = 3 cm/day (Figure 8.1)

Land area required is given by:

$$\text{Area} = 3.65\ Q/L_h \tag{8.14}$$

Where,

Area = Wetted land area, ha;

Q = Design flow, m^3/day; and

L_h = Hydraulic loading, cm/yr.

Therefore,

$$\text{Area} = (3.65\text{x}3,000\ \text{m}^3/\text{day})/(3\ \text{cm/day x } 365\ \text{days/year}) = 10\ \text{ha}$$

From the required area values obtained using both design criteria, it can be seen that the mathematical model presented based on application rate, slope length and application period (Equation 8.14), gives an economical value of 8.2 ha compared to an area of 10 ha with a 3 cm/day hydraulic loading.

Example 8.5

A wastewater has the following characteristics.

Flow rate	= 100 m^3/day
BOD_5	= 250 mg/L
Fecal coliforms	= 6 x 10^5 no./100 mL
Design precipitation	= 1000 mm/year
Percolation	= 400 mm/year
Evapo-transpiration	= 1200 mm/year

a) If the soil type is clay loam, which type of land treatment could be suitable?
b) Determine whether there will be run-off from this land treatment or not, if so calculate the run-off in m^3/day.
c) From the experimental results it was found that the wastewater application cycle to this land should be 3 days of application and 11 days of resting. Application area of the site is 14 ha. Determine the approximate wastewater application rate to be applied, which will not produce run-off.

Solution:

a) As the soil type is clay loam, the suitable type of land treatment will be the OF system (according to Figure 8.1).

b) From Figure 8.1:

Choose a liquid loading rate = 4 in/week
= 4 x 25.4 x 52 mm/year
= 5283 mm/year.

General mass balance equation for land treatment of wastewater is given in equation 8.3:

Design precipitation + wastewater applied = percolation + evapotranspiration + runoff.

$$1000 + 5283 = 400 + 1200 + \text{Runoff}$$

Runoff = 4683 mm/year
Application rate = 4 x 2.54 cm/week

Assuming that the wastewater is applied continuously:

$$\text{Liquid loading rate} = \frac{4 \times 2.54 \times 10^{-2}}{7} \text{ m/day} = 0.0145 \text{ m/day}$$

$$\text{Area required} = \frac{100 \text{ m}^3/\text{d}}{0.0145} = 6889 \text{ m}^2$$

Choose the land area required = 7000 m^2

$$\text{Total run off from site} = \frac{7 \times 10^3 \times 4.683}{365} \text{ m}^3/\text{day} = 89.8 \text{ m}^3/\text{day}$$

c) If there should not be any run off from the land, then from equation 8.3, wastewater applied = 400 + 1200 - 1000 = 600 mm/year which is less than the liquid loading rate in (b).

No. of days in one cycle = 14 days
No. of cycle in year = 26

$$\text{Wastewater flow rate to be applied} = \frac{600}{26} \text{ mm/cycle}$$

No. of days of application/cycle = 3 days

$$\text{Application rate} = \frac{600}{3\text{x}26} \text{mm/day} = 7.7 \text{ mm/day during the 3 days}$$

application period.

If the application area is 14 ha, wastewater flow rate to be applied during the application period is $0.0077 \times 14 \times 10^4$ =1078 m^3/day which is greater than the available flow rate of 100 m^3/day.

Example 8.6

A wastewater has the same characteristics as in Example 8.5. Design an OF system to treat this wastewater so that the treated effluent contains BOD_5 and fecal coliforms less than 50 mg/L and 100 no./100 mL, respectively. The application rate is 0.1 m^3/(hr-m width).

The following information are given

For BOD_5 removal $$\frac{C - 5}{C_o} = 0.72 \exp\left(-\frac{0.02\,z}{q^{0.5}}\right)$$

For fecal coliform removal $$\frac{N}{N_o} = \exp(-K_f t)$$

Where:

N and N_o= effluent and influent fecal coliform concentration, no./100 mL
K_f = fecal coliform removal rate in OF, 0.2/min
t = time of wastewater flow in OF

$$v = \frac{1}{n} R^{2/3} S^{1/2}$$

Where:

v = flow velocity of wastewater during OF treatment, m/sec
R = hydraulic radius of flow, m
S = slope of soil = 0.02
n = coefficient of roughness = 0.38

For BOD_5 removal

$$\left(\frac{50 - 5}{250}\right) = 0.72 \exp\left(-\frac{0.02\,z}{0.1^{0.5}}\right)$$

Slope length, z = 22 m for BOD_5 removal

For fecal coliform removal
Assuming that during wastewater application, the height of wastewater is 5 cm throughout the entire down slope distance

$$\text{Hydraulic radius, } R = \frac{\text{Wetted area}}{\text{Wetted perimeter}}$$

$$\text{Width of the applied area} = \frac{Q}{q} = \frac{100 \text{ m}^3/\text{day}}{0.1 \text{ m}^3/\text{hr-m}} = 41.7 \text{ m}$$

$$\approx 42 \text{ m}$$

$$R = \frac{42\,(0.05)}{42+2(0.05)} = 0.05$$

$$v = \frac{1}{0.38}\,(0.05)^{2/3}\,(0.02)^{1/2} = 0.05 \text{ m/sec}$$

$$\text{Fecal coliform reduction} \quad \frac{100}{6\text{x}10^5} = \exp(-0.2\,t)$$

$$t = 43.5 \text{ min}$$

Slope length for fecal coliform removal = 0.05x43.5x60
= 130.5 m

Choose slope length of the OF area of 130.5 m to provide the treated effluent quality meeting the required BOD_5 and fecal coliform concentrations. Width of the applied area is 42 m.

8.6 SYSTEM MONITORING

Monitoring of land treatment systems involves the observation of significant changes resulting from the application of wastewater. The monitoring data are used to confirm environmental assessment and to determine if any corrective action is necessary to protect the environment or maintain the renovation capacity of the system. The components of the environment that need to be observed include wastewater, groundwater, and soils upon which wastewater is applied and, in some cases, vegetation growing in soils that are receiving wastewater.

Water quality

Monitoring of water quality for land application systems is generally more involved than for conventional treatment systems because non-point discharges of system effluent into the environment are involved. Monitoring of water quality at several stages of a land treatment process may be needed for process control. These stages may be at: the applied wastewater, the renovated water, and the receiving waters - surface water or groundwater.

The water quality parameters and the frequency of analysis will vary from site to site depending on the nature of the applied wastewater. The measured parameters may include:

- Those adversely affect receiving water quality either as drinking water supply or as irrigation water supply,
- Those required by regulatory agencies, and
- Those necessary for system control.

An example of a suggested water quality monitoring program for a large scale SR system is presented in Table 8.11. Renovated water may be recovered as runoff in an overland flow system, or as drainage from underdrains, or groundwater from recovery wells in SR and RI systems.

Groundwater

In groundwater, travel time of constituents is slow and mixing is not as significant as with surface water. Surface inputs near a sampling well will move vertically and arrive at the well much sooner than inputs several hundred meters away from the well. Thus, the groundwater sample represents contributions from all parts of the surface area with each contribution arriving at the well at a different time. A groundwater sample may reflect surface inputs, especially inorganic constituents such as heavy metals, from several years before sampling and have no association with the land application system. Consequently, it is imperative to obtain adequate background quality data and to locate sampling well so that response times are minimized.

If possible, existing background data should be obtained from wells in the same aquifer both beyond and within the anticipated area of influence of the land application system.

Wells with the longest history of data are preferable. Monitoring of background wells should continue after the system is in operation to provide a base for comparison.

In addition to quality, the depth to groundwater should be measured at the sampling wells to determine if the hydraulic response of the aquifer is consistent with what was anticipated. For SR systems, a rise in water table levels to the root zone would necessitate corrective action such as reduced hydraulic loading or adding under drainage. The appearance of seeps or perched groundwater tables might also indicate the need for corrective action.

Soil

In some cases, application of wastewater to the land will result in changes in soil properties. Results of soil sampling and testing will serve as the basis for deciding whether the soil properties should be adjusted by the application of chemical and organic amendments. Soil properties that are important to land treatment of wastewater include: pH, exchangeable sodium percentage or SAR, salinity, nutrient status, and heavy metals.

Soil pH below 5.5 or above 8.5 generally is harmful to most plants. Below pH 6.5 the capacity of soils to retain metals is reduced significantly, the soil with pH above 8.5 generally indicates high sodium content and possible permeability problems.

The levels at which salinity becomes harmful to plant growth depend on the type of crop. Salinity in the root zone is controlled by leaching soluble salts to the subsoil or drainage system.

Crop tissue

Plant tissue analysis is probably more revealing than soil analysis with regard to deficient or toxic levels of elements. All of the environmental factors that affect the uptake of an element are integrated by the plant, thus eliminating much of the complexity associated with interpretation of soil test results. If a regular plant tissue monitoring program is established, deficiencies and toxicities can be determined and corrective action can be taken.

8.6.5 Case studies

The followings are successful case studies for the three-land treatment processes operated at full-scale in the USA.

Table 8.11 Monitoring program for a large slow-rate system (U.S.EPA 1973)

Parameters	Frequency analysis					
	Applied water	Soil	Plants	Groundwater		
				Onsite wells	Perimeter wells	Background wells
Flow	C	-	-	-	-	-
BOD_5 of TOC	W	-	-	Q	Q	Q
COD	W	-	-	Q	Q	Q
Suspended solids	W	-	-	-	-	-
Nitrogen, total	W	2A	A	Q	Q	Q
Nitrogen, nitrate	-	-	-	Q	Q	Q
Phosphorus, total	M	2A	A	Q	Q	Q
Coliforms, total	W	-	-	Q	Q	Q
pH	D	Q	-	Q	Q	Q
Total dissolved solids	M	-	-	Q	Q	Q
Alkalinity	M	-	-	Q	Q	Q
SAR	M	Q	-	Q	Q	Q
Static water level	-	--	-	M	M	M

Legend: C = continuously 2A = Two samples per year
D = Daily A = Annually
Q = Quarterly M = Monthly
W = Weekly SAR = Sodium absorption ratio

Note: Wastewater applied and groundwater should be tested initially and periodically thereafter, as appropriate, for heavy metals, trace organics, or other constituents of environmental concern.

Slow rate process

The city of San Angelo in Texas, USA, owns and operates a wastewater irrigation system with an area of 259 ha and a capacity of 1.9×10^4 m^3/day. The surface soil is clay and clay loam. A hay crop is grown, which is baled and sold, and an average of 500 cattle are grazed on the pasture land (Crites and Pound 1976). Primary treatment of the wastewater precedes surface irrigation, and about 1 week of storage capacity is available when irrigation is not needed. Operating and performance data of this system are shown in Table 8.12.

Rapid infiltration process

At Lake George, New York, a rapid filtration system has been in operation since 1933. The soil type is sand. Wastewater that has received secondary treatment from trickling filters is spread at a rate of about 76 cm/week in the summer. In the winter the application rate is reduced to 18 cm/week because of reduced flows (the city's population fluctuates seasonally). Spreading of the wastewater is continuous, and when ice forms on the surface it is not removed but merely floated by the next wastewater application (Crites and Pound 1976). The operating and performance data are shown in Table 8.13.

Table 8.12 Operating and performance data of an irrigation system in San Angelo, Texas (U.S. EPA 1981)

Annual wastewater loading rate, cm/yr	290
BOD in applied wastewater, mg/L	89
BOD in percolate, mg/L	0.7
BOD removal, %	99
Total N in applied wastewater, mg/L as N	35.4
Total N in percolate, mg/L as N	6.1
N removal, %	83

Table 8.13 Operating and performance data of a rapid infiltration system in Lake George, New York (U.S. EPA 1981)

Hydraulic loading rate, cm/week	58
Summer loading rate, cm/week	76
Winter loading rate, cm/week	18
BOD:N ratio	2:1
Flooding to drying time ratio	1:4
Average BOD loading rate, kg/(ha-day)	53
BOD in applied wastewater, mg/L	60
BOD in percolate water, mg/L	1.2
BOD removal, %	98
Total N in applied wastewater, mg/L as N	11.5 (summer), 12.0 (winter)
Total N in percolate, mg/L as N	7.70 (summer), 7.50 (winter)
Removal of total N, %	33 (summer), 38 (winter)
Soluble phosphate in applied wastewater, mg/L as P	2.1
Soluble phosphate in percolate, mg/L as P	< 1 (summer), 0.014 (winter)
Removal of soluble phosphate, %	> 52 (summer), 99 (winter)
Fecal coliforms in applied wastewater, MPN/100 mL	359,000
Fecal coliforms in percolate, MPN/100 mL	72 (summer), 0 (winter)

Overland flow process

The Campbell Soup Company in Paris, Texas, USA, operates a complete line of heat-processed soups as well as beans and spaghetti products. Its 364-ha overland flow treatment site is planted with water tolerant grasses, such as reed canary grass, perennial rye grass, bermuda grass, tall fescue, and native vegetation (Loehr *et al.* 1979). The soils at the site are sandy loam, clay, and clay loam. Study of the fate of the applied wastewater indicates that about 20% percolates down through the soil, 10-30% is lost by evapo-transpiration, and the remaining 60% returns to the surface stream as runoff (Loehr *et al.* 1979). A sprayed effluent is allowed to flow down 45-60 m slopes ranging from 2 to 6 percent. Grasses are harvested two or three times a year as cash hay crops. The purified water (or runoff) is discharged to the receiving stream via prepared waterways. Table 8.14 shows the design, operation and performance data of this system.

This overland flow system operates as well in winter as in other seasons. Although the removal of phosphorus was about 42%, a later change in the operating procedure, to provide a longer rest period between applications with no change in the total wastewater volume, has increased phosphorus removal to nearly 90% without affecting the BOD or nitrogen removals.

Table 8.14 Design, operation and performance data of overland flow process of the Campbell Soup System, Paris, Texas (Loehr *et al.* 1979; Hinrichs *et al.* 1980)

Length of slope	45-60 m
Slope	2-6%
Size of sprinkler nozzles	6.5 (50 L/min)-8 (80 L/min) mm
Distance between sprinklers	25 m
Operating pressure at sprinkler heads	340-480 kPa
Pretreatment	Screen and degrease
Volume of wastewater treated	22,700 m^3/day
Number of months working in a year	12 months/yr
Wastewater application rate	5-7.6 (cm/wk)
Wastewater application schedule	6-8 hr/day on, 16-18 hr/day off

Parameter	Mean concentration (mg/L)		Removal (%)	
	Influent	Effluent	Concentration	Mass (based on runoff)
TSS	263	16	93.5	98.2
BOD	616	9	98.5	99.1
N	17.4	2.8	83.9	91.5
P	7.6	4.3	42.5	61.5

Chemical analyses of the soil indicate that while the concentration of sodium salts is increasing, it has not reached a level injurious to plants and is not expected to do so in the future. Similarly, nitrates percolating into the groundwater reserve are not expected to build up to the point of concern.

8.7 PUBLIC HEALTH ASPECTS AND PUBLIC ACCEPTANCE

Land treatment of wastewater provides many potential benefits but carries with it the risk of contamination of human and animal food. Land treatment can produce an equal or better quality of effluent than a conventional treatment process, but the public is not aware of it. To be a successful method of wastewater treatment and reuse, the public acceptance of land treatment as a safe and suitable method is very important.

The major health concern is possible pollution by nitrogen, heavy metals, toxic organic compounds and pathogens.

8.7.1 Nitrogen

Excess concentration of nitrate (greater than 10 mg/L, NO_3-N) in drinking water will be the major health concern for infants under 6 months of age. The major pathway of concern in land treatment is conversion of the wastewater nitrogen to nitrate and percolation to drinking water aquifers. All three land treatment methods are quite efficient in nitrification of the wastewater nitrogen. Since OF is a surface discharge system, it is only the SR and RI systems that are of concern for groundwater impacts. Nitrogen is often the limiting factor for design of SR system. Appropriate amount of nitrogen in the percolate can be achieved by selecting proper crop and application rate. The very high loading rates inherent in RI systems result in the greatest potential for nitrate contamination of drinking water in the underground aquifers. The extent of nitrification and nitrate contamination depend on temperature, carbon source, hydraulic loading rate, loading period and physical properties of the soil. To overcome this problem the treatment site can be located far away from drinking water sources, or located above non-drinking water aquifers, or recover the percolate with wells or underdrains for reuse elsewhere. An alternative that has been proposed is to use a two step land treatment consisting of OF system followed by RI system; in this way most of nitrogen could be recovered during the OF process through biomass uptake, nitrification/denitrification, and volatilization.

8.7.2 Heavy metals and other toxic organic compounds

The pathways of potential concern are movement of metals and other toxic organic compounds to drinking water sources and translocation of these compounds through the food chain to human. The plants grown on a land treatment site can accumulate toxic compounds in their leaves, stems and fruits. Removal of metals and toxic compounds is generally effective in all three land treatment methods with that effectiveness retained for considerable period of time. Since the problem of heavy metal and toxic compound pollution is more serious with respect to sludge application to land, this matter will be discussed more in Chapter 9.

8.7.3 Pathogens

The pathogens of concern in land treatment systems are bacteria, parasites and viruses. The major pathways of concern are to the groundwater, internal or external contamination of crops, translocation to grazing animals and human, and off-site transmission via aerosols or runoff. There is no evidence available indicating transmission of parasite diseases from application of wastewater in land treatment systems, because the parasite cysts and eggs will normally settle out during pre application treatment or in storage ponds. But there are chances of human infection by parasite diseases if the land treatment area is accessible to the public. It has been found that *Ascaris* ova will survive in soil for long period and investigations on a site in France proved the presence of ascaris ova in soil.

Concerns, with respect to crop contamination, focus mainly on surface contamination and then persistence of the pathogens until consumed by human or animals or the internal infection of the plant via the roots. As shown in Figure 8.13, pathogen survival periods on leaves and fruit crops tend to be shorter than the growth periods of most of these plants (Strauss 1986). In soil, however, survival of viruses, *Salmonellae* bacteria, and *Ascaris* eggs may exceed the growth period of crops (Figure 8.14). Viable pathogens are therefore more likely found on root crops and soil than on leaf crops.

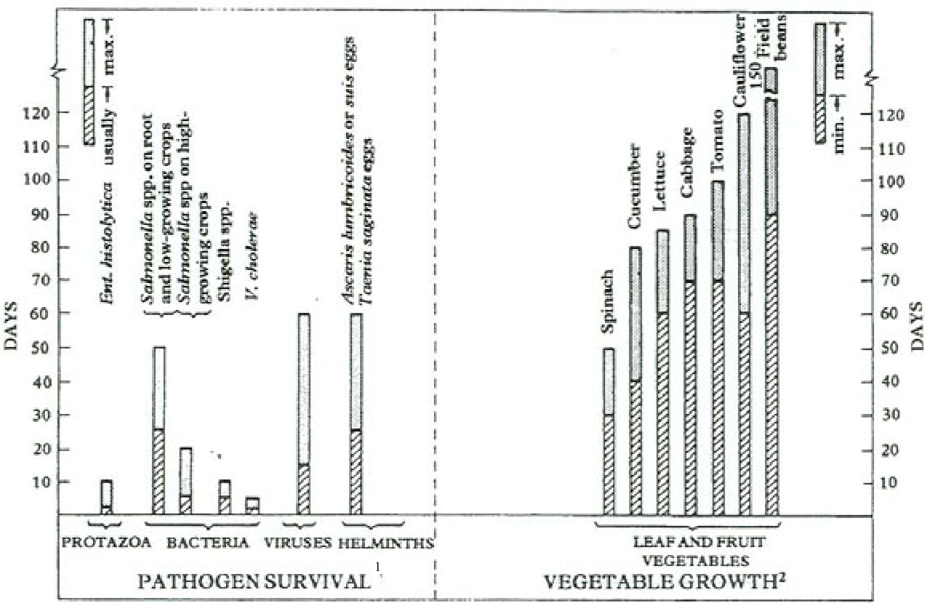
Human or animal infection can be reduced by taking preventive methods such as prohibiting the consumption of raw vegetables grown on land treatment sites, and allowing a period of two weeks or more after application of wastewater before animals are allowed to graze. This will allow sunlight to kill most of the fecal bacteria and viruses. As time and temperatures have significant effects on pathogen die-off (Figure 3.1), prolonged storage of wastewater or sludge to be applied to crops will help minimize the public health risks. Strauss (1986) suggested storage periods for pathogen inactivation in excreta, as shown in Table 8.12.

Runoff from a land treatment site might be a potential pathway for pathogens transport; but this is not a problem in RI system. Groundwater contamination has the highest potential for RI system due to the high hydraulic loading rate and coarse texture of the receiving soils.

Table 8.15 Tentative recommendations for excreta storage periods in warm climates

Storage period	Hygienic quality acheived
≥ 2 days	Inactivation of *Clonorchis* and *Opisthorchis* eggs
≥ 1 month	Complete inactivation of viruses, bacteria and protozoa (except, possibly, Salmonella on moist, shaded soil); inactivation of schistosome eggs
≥ 4 months	Inactivation of nematode (roundworm) eggs e.g. hookworm and whipworm (Trichuris); survival of a certain percentage (10-30%) of *Ascaris* eggs
≥ 12 months	Complete inactivation of *Ascaris* eggs

From Strauss (1986); reproduced by the permission of IRCWD



1) Determined under widely varying conditions
2) Maturation period from transplanting or from sowing if not transplanted

Figure 8.13 Pathogen survival on crops vs. vegetable growth periods in warm climates (from Strauss 1986; reproduced by permission of IRCWD, Switzerland)

The potential for transport of pathogens by aerosols from land treatment sites has been the most controversial issue in recent years. The main reason for this controversial is due to the unawareness of the difference between aerosols and sprinkler droplets. To avoid bacterial and virus transport through aerosols it is preferable to locate the treatment site away and down wind from the residential areas, when sprinklers are used for distribution of wastewater. Depending on the wind speed and topography, pathogen-carried aerosols can travel several hundred meters away from the land treatment site.

With respect to epidemiological study of land treatment of wastewater, it appears from Table 2.26 that the relative health risks due to intestinal nematodes are high, followed by bacterial and viral infections. The microbiological quality guidelines (Table 2.27) suggest that the density of viable eggs of intestinal nematodes (*Ascaris, Trichuris* and hookworms) be equal to or less than 1 per L of wastewater to be used for both restricted and unrestricted irrigation. With respect to fecal coliforms, their density should be less than 1000 no. per 100 mL of wastewater to be used for unrestricted irrigation. A relaxed standard of fecal coliform density is applied to wastewater to be used for restricted irrigation.

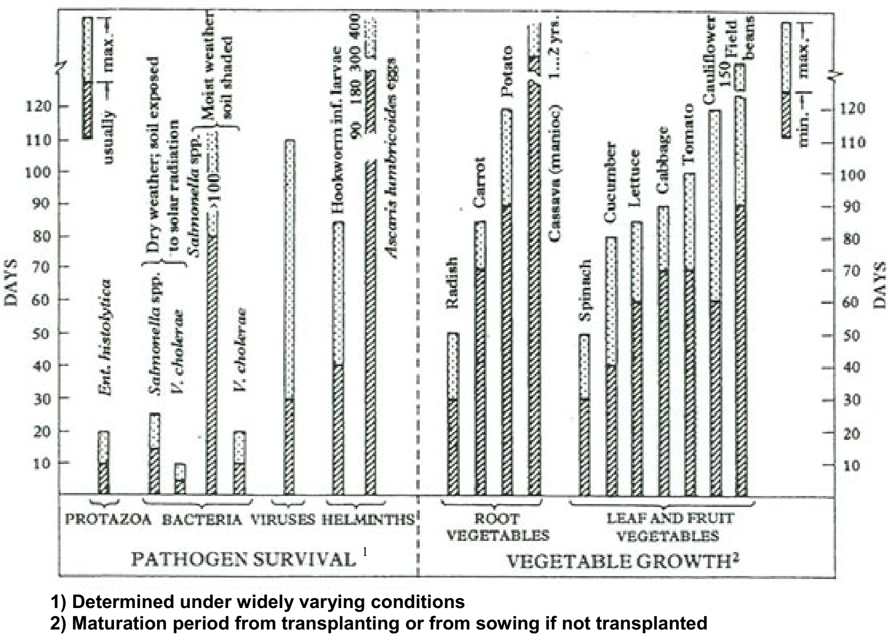


Figure 8.14 Pathogen survival in soil vs vegetable growth periods in warm climates (from Strauss 1986; reproduced by the permission of IRCWS, Switzerland)

Land treatment of wastewater has been in practice in many parts of the world for decades. Where land is available, this method of wastewater treatment is generally attractive because it is low-cost, easy to operate and maintain, and can yield some financial return from the sale of marketable crops. Similar to other waste recycling options, the public, depending on their socio-economic conditions, is likely to accept and support this method of wastewater treatment if public health risks are kept to a minimum and the reuse is directed towards non-body contact (see section 1.4). The current effort to improve design and operation criteria for land treatment together with regulatory standards for effluent discharge should make the method of wastewater treatment by land a viable method compatible with other conventional methods.

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8.9 EXERCISES

8.1 Discuss the functions of vegetation in the land treatment process. Give the criteria to be used in selecting a type of vegetation (or crop) for a land treatment process.

8.2 a) You are to find out the indigenous types of soil and crops in your city. Based on this information, suggest a suitable process of land treatment of wastewater you would select for the city.

In practice, what are the other information needed for the selection of the type of land treatment process?

b) If the city agrees to employ the land treatment process recommended in a), you are to determine the following:

- Land area requirement for wastewater treatment
- Method of wastewater application
- Wastewater application rate (hydraulic and organic loading rates), and the periods of wastewater application and resting
- expected characteristics of the treated wastewater
- harvesting frequency of the crop
- lay-out (or schematic diagram) of the land treatment system, including the pre-treatment units.

8.3 Among the three processes of land treatment, i.e. slow-rate, rapid infiltration and overland flow, discuss which process is most effective in treating wastewaters containing the following constituents:

a) Nitrogen (in organic and ammonium forms)
b) Phosphorus
c) Heavy metals
d) Fecal coliform bacteria

e) Helminth ova
f) Toxic organic compounds (e.g. trichloroethylene)

8.4 A wastewater is generated at a flow rate of 1000 m^3/day. An irrigation (slow-rate) system is to be designed to treat this wastewater with an application rate of 5 cm/week. What is the required land area if the system is operated all year round? What is the required land area if the system is designed for 40 weeks/yr?

A sprinkler system is chosen for application of the wastewater. The sprinklers are spaced in a square grid pattern of 20 m x 20 m, and each sprinkler discharges at a rate of 1.6 L/s. How many sprinklers are needed for the year-round operation? What is the application rate in cm/h? How many hours should the system be operated each week to achieve the application rate of 5 cm/week?

8.5 A rapid infiltration system is designed for an application rate of 30 m/yr. The system is run throughout the year by applying the wastewater every Monday of a week followed by 6 days of resting. The wastewater contains 50 mg/L of BOD_5. What are the average BOD_5 loading rates annually, weekly and on Monday? Over the 7-day cycle, what is the average BOD_5 loading rate in kg/(ha-day)? What is the BOD_5 loading on Monday in kg/(ha-day)? If the wastewater flow is 2500 m^3/day, with respect to the above application cycle, calculate the land area required.

8.6 A design equation for the overland flow process is given in Equation 8.13:

a) Discuss the merits and drawbacks of this equation in predicting the wastewater treatment efficiency;
b) Discuss whether equation 8.13 can be applied to predict fecal coliform removal in the overland flow process;
c) Discuss whether equation 8.13 can be applied to predict wastewater treatment efficiency for the slow-rate and rapid infiltration processes.

8.7 The soil of a municipality located in Southeast Asia is found to have an infiltration capacity of 50 cm/day. It is planned to employ the rapid infiltration (RI) system to treat this municipal wastewater whose flow rate is 2000 m^3/day. If only 1 ha of land is available for construction of the RI system, determine:

a) the required volume of the wastewater storage pond,
b) whether flooding will occur from this wastewater application or not?
c) possible environmental impacts to be resulted from the RI application.

Note: the following RI application procedures is recommended
Wastewater application = 4 days
Resting period = 10 days

8.8. A municipality in Southeast Asia plans to use part of its wastewater to irrigate a 1-ha land for growing corns. The following information are given:

Applied N concentration	= 30 mg/L
N uptake of corns	= 200 kg/(ha-year)
Denitrification, as % of applied N loading	= 20
Precipitation (P_p) – evapotranspiration (ET)	= 30 cm/year
Runoff	= 0

a) To prevent excessive N contamination of the groundwater, the percolate N of this wastewater irrigation should be equal to or less than 10 mg/L. Determine the amount of wastewater (in m^3/year) that should be applied to this 1-ha land to support corn growth.
b) If, due to a severe drought in a particular year, the P_p – ET is -30 cm/yr, but the municipality still applies the same amount of wastewater as in a) to this 1-ha land for corn growth. Determine the concentration of percolate N in this particular year and the environmental impacts to be resulted from this practice.

8.9 A municipality in Southeast Asia produces wastewater with the following characteristics:

Flow rate	= 2,000 m^3/day
BOD_5	= 100 g/m^3
NH_4-N	= 20 g/m^3
Fecal coliforms	= 10^3 no./100 mL

a) You are to design an overland flow (OF) unit to treat this wastewater to produce an effluent having BOD_5 and NH_4-N concentrations of less than 20 and 5 g/m^3, respectively. Give dimension (length × width) and slope height and draw a schematic diagram of this OF unit or plots. The design OF system is based on Equation 8.13.

b) If this municipality is located on a flat plain land, suggest measures to make the OF site suitable for wastewater treatment and a method to reuse of the OF effluent that would be both acceptable by the students and microbiologically safe for them.

8.10 An agro-industry factory in northeast Thailand produces wastewater with the following characteristics:

Flow rate	= 20 m^3/day
N concentration	= 20 g/m^3

a) The factory plans to use its wastewater to grow corns. Determine the land area of the corn field that can be irrigated by this wastewater so that the percolate N is equal to or less than 10 mg/L (to prevent methamoglobinemia).

Note: N uptake of corns = 200 kg/(ha-year)
Denitrification = 20% of applied N loading
Precipitation (P_P) – Evapotranspiration (ET) = -20 cm/yr
Runoff = 0

b) If, due to an unusual weather in the year 2004, the P_p-ET is equal to + 20 cm/yr, but the factory still applies all its wastewater to this same land area of the cornfield. What would be the effects of this practice on corn growth and groundwater N concentration? Give reasons.

9

Land treatment of sludge

Land treatment of sludge has become a method that is being increasingly considered by many municipalities throughout the world. It offers the advantage of recycling nutrients back to the land at low cost, and of reclaiming lands being spoiled by strip mining, deforestation and too much application of inorganic fertilizers. Sludge is normally stabilized by anaerobic digestion or other suitable means before application on land. Such stabilization eliminates obnoxious odours and fly problems. Yield of grain and forage crops are increased by the nutrients and water supplied by irrigating with digested sludge. Organic matter in digested sludge accumulates in and imparts favourable characteristics to soils because of its normally high humus content. “Biosolid” is a term commonly used to describe sludge solids that are suitable for beneficial land application or digestion to produce compost and/or biofuels as described in Chapters 3 and 4, respectively.

Sludge production in the U.S. in 2005 was estimated to 7.6 millions dry tons, and this quantity is expected to increase to 8.3 millions dry tons by 2010 (U.S. EPA 1999). Table 9.1 shows the various means of sludge disposal in which smaller wastewater treatment plants tend to use land application more than do large wastewater treatment plants. The total production of sewage sludge per year in the 15 original European Union countries was estimated to be 10.7 million tons of dry matter in 2005 (www.mapa.es/app); this sludge is disposed of as follows (Kofoed 1984):

- 29 % is used in agriculture
- 45 % is disposed of on controlled refuse dump
- 7 % is disposed of by incineration
- 19 % is discharged in the sea

Data on sludge production in developing countries are not readily available because most cities do not have adequate sewerage systems for wastewater transportation to central treatment plants. However, it can be estimated that each person generates 25-40 kg dry matter of sludge per year or about 800 kg wet sludge (95% water content) per year.

Table 9.1 Estimated distribution of municipal sludge in 1980 (U.S. EPA 1983)

	Percent of total sludge	
Disposal Practice	U.S.A.	European Community
Beneficial land application	36	32
Landfills	38	48
Incineration	16	13
Surface disposal	10	2
Sea disposal	-	5

9.1 OBJECTIVES, BENEFITS AND LIMITATIONS

There are four major categories of sludge land application systems:

1. Agricultural utilization: Sludge is used as a source of fertilizer nutrients and/or as a soil amendment.
2. Forest utilization: Sludge is used to enhance forest productivity.
3. Land reclamation: Sludge is used to reclaim disturbed land, such as strip mined area for the purpose of re-vegetation, or to reclaim seashore land.
4. Land disposal: Sludge is applied to soils, with or without vegetation, for the primary purpose of sludge disposal. Crop production or improvement of soil characteristics is of secondary importance.

The physical characteristics of various types of sludge are given in Table 9.2. Well-digested sludge is inoffensive and quite suitable for land application. Other types of sludge are mostly not well stabilized and have offensive odours. Typical chemical compositions of raw and digested sludge are presented in Table 9.3. Digested sludge usually contains less percentage of volatile solids and protein than raw sludge, however the former types of sludge have high contents of nutrients (N, P, and K). Table 9.4 gives the nutrient contents of several sludge types in USA, which indicates the suitability of using this sludge in agricultural production and land reclamation. Since many municipalities can offer their sludge at practically no cost to the farmers, a significant cost saving is effected both for the farmers and the municipality which produces the sludge. However, the cost of sludge transportation from a treatment plant to a land application site and proper application of sludge to land (see section 9.2) can be expensive, in some cases.

Table 9.2 Physical characteristics of various types of sludge (Loehr and Jewell 1979)

Sludge	Colour	Other physical properties	Odour	Digestibility (amenability to further biological stabilisation)
Primary sedimentation	Grey	Slimy	Extremely offensive	Readily digested
Chemical precipitation (primary)	Black, red surface if high in iron	Slimy, gelatinous, gives off considerable gas	Offensive	Slower rate than primary sedimentation
Activated sludge	Brown, dark if nearly septic	Flocculent	Inoffensive, earthy when fresh, putrefies rapidly	Readily digested
Trickling filter humus	Brownish	Flocculent	Relatively inoffensive, decomposes slowly	Readily digested
Digested sludge	Dark brown to black	Contains very large quantity of gas	Inoffensive if thoroughly digested; like tar or loamy soil	Well stabilized
Septic tank sludge	Black		Offensive (H_2S) unless very long storage time	Mostly stabilized

Table 9.3 Chemical composition of raw and digested sludge (Loehr *et al.* 1979)

Item	Raw primary sludge[a]		Digested sludge[b]	
	Range	Typical	Range	Typical
Total dry solids (TS), %	2.0 – 7.0	4.0	6.0 – 12.0	10.0
Volatile solids (% of TS)	60 – 80	65	30 – 60	40.0
Grease and fats (ether-soluble, % of TS)	6.0 – 30.0	-	5.0 – 20.0	-
Protein (% of TS)	20 – 30	25	15 – 20	18
Nitrogen (% of TS)	1.5 – 4.0	2.5	1.6 – 6.0	3.0
Phosphorus (P_2O_5, % of TS)	0.8 – 2.8	1.6	1.5 – 4.0	2.5
Potash (K_2O, % of TS)	0 – 1.0	0.4	0.0- 3.0	1.0
Cellulose (% of TS)	8.0 – 15	10.0	8.0 – 15.0	10.0
Silica (SiO_2, % of TS)	15 – 20	-	10.0 – 20.0	-
pH	5.0 – 8.0	6.0	6.5 – 7.5	7.0
Alkalinity (mg/L as $CaCO_3$)	500 – 1,500	600	2,500 – 3,500	3,000

[a] refer to sludge settled in primary sedimentation tanks
[b] Mostly refers to anaerobically digested sludge

Sewage sludge when applied to soils provides a source of plant nutrients and it is an effective soil amendment. Sludge applied to land provides major plant nutrients such as N, P, K; micro-plant nutrients such as Cu, Fe and Zn; and organic matter for improving the soil structure (e.g. better aeration and water holding capacity). The effectiveness of sludge as a soil improving agent depends upon the composition of the sludge, the characteristics of the soil to which it is applied and the plant species to be grown.

Some of the limitations in using sludge as fertilizer include the fluctuation of nutrient content. The nutrient content of municipal sludge varies considerably, and N, P, and K levels are about one-fifth of those found in typical chemical fertilizers. Much of the N and P in sludge are in organic combination that should be mineralized before becoming available to plants. The rate of mineralization for N and P in soil is dependent upon local conditions such as soil type, temperature, soil pH, soil water and other soil chemical and physical characteristics. Certain sludge can be quite inert and create problems in the consideration of ultimate disposal techniques. In addition, sludge application on land may create odor problems and potential health hazards due to the presence of some toxic compounds and pathogens contained in the sludge itself.

Table 9.4 Concentration of organic carbon (C), total nitrogen (TN), phosphorus (P), ammonia (NH_4^+), nitrate (NO_3^-), sulphur (S) and potassium (K) in sewage (U.S. EPA 1983)

Components	Sludge type[b]	Number of samples	Range	Medium[c]	Mean
Organic C, %	Anaerobic	31	18 – 39	26.8	27.6
	Aerobic	10	27 – 37	29.5	31.7
Total N,%	Anaerobic	85	0.5 – 17.6	4.2	5.0
	Aerobic	38	0.5 – 7.6	4.8	4.9
NH_4^+- N, mg/kg	Anaerobic	67	120– 67,600	1,600	9,400
	Aerobic	33	30 – 11,300	400	950
NO_3^- - N, mg/kg	Anaerobic	35	2 – 4,900	79	520
	Aerobic	8	7 – 830	180	300
Total P, %	Anaerobic	86	0.5 – 14.3	3.0	3.3
	Aerobic	38	1.1 – 5.5	2.7	2.9
Total S, %	Anaerobic	19	0.8 – 1.0	1.1	1.2
	Aerobic	9	0.6 – 1.1	0.8	0.8
K, %	Anaerobic	86	0.02 – 2.64	0.30	0.52
	Aerobic	37	0.08 – 1.10	0.39	0.46

[a] Concentration and percentage composition are on a dried solids basis
[b] Other includes lagooned, primary, tertiary and unspecified sludges.
[c] Median concentration are reported to be better measures of 'typical' concentration than the arithmetic mean
- Not reported.

9.2 SLUDGE TRANSPORT AND APPLICATION PROCEDURES

The important elements of system design of land treatment of sludge are: modes of sludge transport, sludge application procedures, and sludge application rates. The first two elements will be described in this section while section 9.3 will discuss the third element.

9.2.1 Mode of sludge transport

Table 9.5 shows the various methods to handle and transport sludge from a source to land application/disposal site. Transportation may be accomplished by pipeline (gravity flow or pressured), tank truck, barge, or conveyor rail. Sludge characteristics (e.g. solid contents), sludge volume, elevation differences, transport distance and land availability are important factors in selecting a method of sludge transportation. As shown in Table 9.6, liquid sludge (1-10% solid contents) is generally suitable for any modes of sludge transport, while semi-solid or solid sludge, having high solid content (8-80%), should be transported only by trucks or rail hopper cars.

Tank trucks are currently widely used to transport and apply sludge on land because they afford flexibility in the selection of land application sites. Usually, a storage facility for sludge is provided at the land application site.

Table 9.5 Sludge solids content and handling characteristics (Knezek and Miller 1976)

Type	Solid contents (%)	Handling methods
Liquid	1 – 10	Gravity flow, pump, tank support
Semi- solid (‘wet’ solid)	8 – 30	Conveyor, auger, truck transport (water tight box)
Solid (‘dry’ solid)	25 – 80	Conveyor, bucket, truck transport

9.2.2 Sludge application procedures

Similar to the mode of sludge transport, the selection of sludge application systems and equipments depends on: type of the sludge (liquid, semi-solid or solid), quantity, a real application rate, frequency of application, topography of the applied area, and time of the year. Table 9.7 gives the various sludge application methods and the equipments required for the application. The irrigation methods such as sprinkling, ridge and furrow (Figure 8.2) and overland flow (Figure 8.4), are similar to those described in Chapter 8 "Land Treatment of Wastewater". Sprinkling systems, applicable to only liquid sludge, require less preparation and can be used with a wide variety of crops. Ridge-and-furrow and overland flow are suitable to level land and sloped land, respectively; they also minimize aerosol-related pathogens and aesthetic problems.

Tank trucks, farm tank wagons and tractors are also effective in applying sludge on crop lands in which sludge is pumped from roadway onto the field. Commercial tank trucks with plow furrow cover are available where sludge is discharged in furrow ahead of plow mounted on rear of the trucks.

Table 9.6 Transport modes for sludge (Knezek and Miller 1976)

Type	Characteristics
Liquid sludge	
Rail tank car	100 wet tons (24,000 gal[a]) capacity; suspended solids will settle while transit.
Barge	Capacity determined by waterways; Chicago has used 1,200 wet tons (290,000 gal) barges.
Pipeline	Need minimum velocity of 1 f.p.s. (30 m/s) to keep solids in suspension; friction decreases as pipe diameter increases (to the fifth power); buried pipelines suitable for one-year use.
Vehicles	
Tank truck	Capacity-up to maximum load allowed on road Can have gravity or pressurized discharge. Field trafficability can be improved by using floatation tires.
Farm tank wagon and tractor	Capacity: 830 – 3,000 gal. Principal use would be for field application
Sem-solid or solid sludge	
Rail hopper car	Need special unloading sites and equipment for field application
Truck	Commercial equipment available to unload and spread on ground need to level sludge piles if dump truck is used.

[a] 1 gallon = 3.785 L

Table 9.7 Application methods and equipments for liquid and some semi-solid sludge

Method	Characteristics	Topographical and seasonal suitability
Irrigation		
Spray (Sprinkler)	Large orifice required on nozzle; large power and lower labour requirements; wide selection of commercial equipment available; sludge must be flushed from pipes when irrigation completed	Can be used in sloping land; can be used year-round if the pipe is drained in winter; not suitable for application to some crops during growing season; odour (aerosol) nuisance may occur.
Ridge- and- furrow	Land preparation needed; lower power requirements than spray.	Between 0.5 and 1.5 % slope depending on percentage solids; can be used from rows of crops.
Overland flow	Used on sloping ground with vegetation with no runoff permitted: suitable for emergency operation; difficult to get uniform aerial application.	Can be applied from ridge roads.
Tank truck	Capacity 500 to more than 2,000 gal; large volume trucks will require floatation tires; can use with temporary irrigation set up; with pump discharge can spray from roadways on to field.	Tillable land; not usable with row crops or on soft ground.
Farm tank wagon and tractor	Capacity 500 to 3,000 gal; larger volume will require floatation tires; can use with temporary irrigation set-up; with pump discharge can spray from roadways on to field.	Tillable land, not usable with row crops or on soft ground.
Flexible irrigation hose with plow furrow or disc cover	Use with pipelines or tank truck with pressure discharge; hose connected to manifold discharge on plow or disc.	Tillable land; not usable on wet or frozen ground.
Tank truck with plow furrow cover	500 gal. Commercial equipment available; sludge discharged in furrow ahead of plow mounted on rear of four wheel-drive truck.	Tillable land, not usable on wet or frozen ground.

Table 9.7 Application methods and equipments for liquid and some semi-solid sludge (continued)

Method	Characteristics	Topographical and seasonal suitability
Plow furrow cover	Sludge discharged into furrows ahead of plow mounted on tank trailer- application of 170 – 225 tons/acre; or sludge spread in narrow band on ground surface and immediately plowed under- application of 5-125 wet tons/acre.	Tillable land, not usable on wet or frozen ground.
Subsurface injection	Sludge discharged into channel opened by a tillable tool mounted on tank trailer; application rate 25 – 50 tons/acre; vehicle should not traverse injected area for several days.	Tillable land, not usable on wet or frozen ground.

1 acre = 0.405 ha
1 ton/acre = 2,470 kg/ha
1 gallon = 3.785 L
From Knezek and Miller (1978)

9.3 SYSTEM DESIGN AND SLUDGE APPLICATION RATES

The design of land treatment of wastewater and sludge is usually based on the limiting design parameter (LDP). LDP is the design value in which other constraints such as nutrient requirements or public health problems will be overcome. For example, the annual sludge application rate on an agricultural land may be determined by N or P requirement, and the useful life of the site may be limited by cadmium (Cd) loading. Sludge should be applied to agricultural land at a rate equal to the N uptake rate of the crop unless less application rates are required because of cadmium limitations. The basis for N loading criteria is to minimize nitrate leaching to groundwater. The annual limit for Cd loading is to minimize crop uptake and the potential long-term, sub-clinical adverse effects on human health. The lifetime limit of a land application site is established on the basis of maximum cumulative loadings of heavy metals such as lead (Pb), zinc (Zn), copper (Cu), and nickel (Ni) and Cd. These limits are designed to allow for growth and use of food-chain crops at future dates.

Since the liquid content of sludge is typically low, the hydraulic capacity of the site soils is seldom the LDP for design. An exception might be toxic and hazardous waste sites where very permeable soils would permit too rapid percolate movement.

A preliminary estimate of the land area required for screening purposes can be determined for municipal sludge with Table 9.8. Estimates of soil treatment area for industrial sludge should be based on the critical LDP such as metal concentration, etc. Slope limitation for the land application of the sludge is given in Table 9.9.

For the agricultural utilization of sludge, the design approach is based on the utilization of sludge as a supplement or replacement for commercial fertilizers. As a result the annual application is based on either the N or P needs of the crop in a particular soil. In addition, both the annual and cumulative sludge loadings must be consistent with regulatory limits on pathogens and metals. Table 9.10 summarizes the U.S. EPA limits on cumulative heavy metal loadings for agricultural land as a function of soil cation exchange capacity (CEC). CEC has been employed as an indicator of soil properties because it has been shown experimentally that most metals in sludge-amended soils are not present as an exchangeable cation, or these metals are not exchangeable with a neutral salt. Therefore soil with a higher CEC value would minimize the plant availability of sludge-borne metals more than soil with a lower CEC value (U.S. EPA 1983).

In general the CEC ranges of less than 5, 5-15, and more than 15 meq/100 g correspond to sands, sandy loams, and silt loams, respectively.

Table 9.8 Estimated land area for municipal sludge application

Options	Application period	Reported range (dry tons/ha)	Typical rate (dry tons/ha)
Agricultural	Annual	0.4 – 12	2
Forest	One application or at 3-5 year interval	1.6 – 40.5	8
Site reclamation	One application	1.2 – 81	20

From Reed and Crites (1984); reported by permission of Noyes Publications, from *Handbook of Treatment Systems for Industrial and Municipal Wastes.*

Table 9.9 Recommended slopes for sludge sites (U.S. EPA 1983)

Slope (%)	Comment
0 – 3	Ideal
3- 6	Acceptable for surface application of injection
6 – 12	Applicable for injected liquid sludge
12- 15	Immediate incorporation of all sludge, and effective runoff control are necessary

Based on scientific risk-assessment evaluation aimed at limiting human and ecological exposure to sludge contaminants, in relation to the current sewage sludge and disposal regulations the U.S. EPA has implemented the new land application limits for the 10 heavy metals, as shown in Table 9.11. These limits do not mention about soil CEC, but the cumulative limits for Pb and Ni are lower than those reported in Table 9.10 (at CEC greater than 15 meq/100g) and Table 9.12 (for Pb), while the cumulative limits for other heavy metals (Cd, Cu, and Zn) are higher. Table 9.11 classifies sludge quality as “ceiling concentration limits” and higher quality pollutant concentration limits”. Sludge quality classifications and application restrictions are defined as follows:

1. If a sludge meets the “high quality” metal concentration limits, it can be land applied provided that the application rate does not exceed annual pollutant loading rates as shown in Table 9.11.
2. If a sludge does not meet the “high quality” limits but does meet the ceiling concentration limits, the sludge can be land applied provided that the cumulative pollutant loading rates as defined in Table 9.11 are not exceeded (in addition to annual pollutant loading rates).
3. If a sludge does not meet ceiling concentration limits, it cannot be land applied.

Table 9.10 Recommended cumulative limits for metals of major concern applied to agricultural cropland (U.S. EPA 1983)

Metal	Soil cation exchange capacity (meq/100 g)[a,b]		
	< 5 kg/ha	5 – 15 kg/ha	> 15 kg/ha
Pb	560	1,120	2,240
Zn	280	560	1,120
Cu	140	280	560
Ni	140	280	560
Cd	5	10	20

[a] Interpolation should be used to obtain values in the CEC range 5-15
[b] Soil must be maintained at pH 6.5 or above

Table 9.11 U.S. land application pollutant limits (Walsh 1995)[a]. Reproduced by permission of IWA Publishing

Pollutants	Ceiling concentration limits (mg/kg)	Cumulative pollutant loading rates (kg/ha)	'High quality' pollutants concentration limits (mg/kg)	Annual pollutant loading rates (kg/ha-yr)
Arsenic	75	41	41	2.0
Cadmium	85	39	39	1.9
Chromium	3,000	3,000	1,200	150
Copper	4,300	1,500	1,500	75
Lead	840	300	300	15
Mercury	57	17	17	0.85
Molybdenum	75	18[b]	18[b]	0.90
Nickel	420	420	420	21
Selenium	100	100	36	5.0
Zinc	7,500	2,800	2,800	140

[a] All weight are on a dry weight basis and ceiling concentration limits represent absolute values. 'High quality' pollutants loading rates represent monthly averages.
[b] In February 1994, the U.S. EPA withdrew the molybdenum value of 18 mg/kg pending further review of scientific information supporting a higher concentration.

Table 9.13 shows the concentration limits of heavy metals in sewage sludge used for land application in several Europe countries. These limits put stringent standards on Cd, Hg, and As similar to those of Table 9.11.

Other guidelines for sludge application for fruits and vegetable production are given in Table 9.12. It is required that soils at sludge application sites be maintained at a soil pH of 6.5 or above. Information on fertilizer recommendations for a particular crop in a specific location can be obtained from agricultural experiment extension stations located in the province or country (see Table 8.7). The design is then based on meeting either the N or P needs.

Optimum yields and crop production may then require supplemental fertilization for the other nutrients (N, P and K) (Reed and Crites 1984).

Table 9.12 Summary of joint EPA/FDA/USDA guidelines for sludge application for fruit and vegetable production (U.S. EPA 1983)

Annual and cumulative Cd rates

Annual rate should not exceed 0.5 kg/ha. Cumulative Cd loadings should not exceed 5, 10, or 20 kg/ha, depending on soil pH and CEC values of <5, 5 to 15, and >15 meq/100 g, respectively.

Soil pH

Soil pH (plow zone - top 6 in) should be 6.5 or greater at time of each sludge application.

PCB's

Sludges with PCB concentrations greater than 10 mg/kg should be incorporated into the soil.

Pathogen reduction

Sludge should be treated by pathogen reduction process before soil application. Waiting period of 12 to 18 months before a crop is grown may be required, depending on prior sludge processing and disinfection.

Use of high-quality sludge

High-quality sludge should not contain more than 25 mg/kg Cd, 1,000 mg/kg Pb, and 10 mg/kg PCB (dry weight basis).

Cumulative lead application rate

Cumulative Pb loading should not exceed 800 kg/ha.

Pathogenic organisms

A minimum requirement is that crops to be eaten raw should not be planted in sludge-amended fields within 12 to 18 months after the last sludge application. Further assurance of safe and wholesome food products can be achieved by increasing the time interval to 36 months.

Physical contamination and filth

Sludge should be applied directly to soil and not directly to any human food crop. Crops grown for human consumption on sludge-amended fields should be processed with good food industry practices, especially for root crops and low-growing fresh fruits and vegetables.

Soil monitoring

Soil monitoring should be performed on a regular basis, at least annually for pH. Every few years, soil test should be run for Cd and Pb.

Choice of crop type

The growing of plants that do not accumulate heavy metals is encouraged.

Note:FDA = U.S. Food and Drug Administration USDA = U.S. Department of Agriculture

In addition to Table 9.12, the U.S. EPA also classifies sludge quality based on indicator bacteria. The class A indicator standard is less than 1000 faecal coliforms per gram of dry solids and the class B indicator standard is less than 3 million faecal coliforms per gram of dry sludge solids (Walsh 1995). If a sludge contains about 1% solids, the class A standard is apparently similar to the WHO standard for unrestricted irrigation (Table 2.27), and there are no use restrictions placed on sludge that meet the class A requirements. Because the class B sludge poses greater health risks, the U.S.EPA imposes more use restrictions than those outlined in Table 9.12, e.g.

1. food crops that receive a sludge application cannot be harvested for periods ranging from 14 – 38 months afterwards, depending on the type of crop grown and the method of application
2. pasture lands that receive sludge cannot be grazed for 30 days
3. turflands are not allowed to be harvested within 12 months of application, and
4. public lands that receive sludge application will have access restricted for 30 days in low-exposure area and up to 1 year for high exposure areas.

Table 9.13 Concentration limits of heavy metals in sewage sludge used for land application in some European countries (cited in Rulkens *et al.* 1989). Reproduced by permission of Chapman and Hall

	Concentration Limit (mg/kg dry solids)							
	Zn	Cu	Pb	Cr	Ni	Cd	Hg	As
Netherlands	2,000	600	500	500	100	5	5	10
France	3,000	1,000	800	1,000	200	40	10	-
Germany	3,000	1,200	1,200	1,200	200	20	25	-
Norway	3,000	1,500	300	200	100	10	7	-
Sweden	10,000	3,000	300	1,000	500	15	8	-
Finland	5,000	3,000	1,200	1,000	500	30	25	-
Scotland	10,000	1,000	800	800	250	20	7.5	150

9.3.1 Sludge Application Rates

The application rates of sludge to cropland vary according to the nutrient requirements of the crop, existing soil characteristics (e.g. drainage, nutrient level, heavy metal content), climate, and the characteristics of the sludge. In all cases, the application rate should be such that:

1. Crop production and quality are not decreased.
2. The soil does not build up excessive organic material or heavy metals.

3. Nutrients and excessive salts do not leak into surface or subsurface water supplies.
4. Crops are not contaminated with pathogens that will become health risks to the farm operators and consumers.

Application rate based on heavy metal concentrations

It is apparent from Table 9.10 that sludge with significant metal concentrations might have an annual application limited by Cd. According to this table, the maximum lifetime application of cadmium is 5 kg/ha for soils with a cation exchange capacity (CEC) less than 5 meq/100 g, 10 kg/ha for soils with a CEC between 5 and 15 meq/100 g, and 20 kg/ha for soils with CEC exceeding 15 meq/100 g. A further restriction is that sludge containing Cd in excess of 25 mg/kg should not be applied to sites where tobacco, leafy vegetables or root crops are grown. The state of California, U.S.A., additionally recommends that the annual application of Cd from sludge should not exceed 0.5 kg/ha on land use for production of crops grown for human consumption (Crites and Richard 1987).

Application rate based on nitrogen

Since much of the sludge nitrogen is in the organic form, as shown in Tables 9.3 and 9.4, it is not all readily available to the plants. Other forms of nitrogen in sludge are ammonia nitrogen and very little nitrate. When applied on land, part of organic nitrogen will be mineralized or biologically converted into ammonia and/or nitrate to become available to the plants. Table 9.14 contains suggested mineralization rates for organic nitrogen present in a few types of sludge. The organic nitrogen not mineralized in the first year (or the first growing season) will be mineralized in the subsequent years according to these mineralization rates. Because of the high temperatures prevailing in the tropics, Sripanomtanakorn and Polprasert (2002) found the percent N mineralization of anaerobically digested sludge in the first growing season to be 27-42%, higher than the 20% value shown in Table 9.14.

Under a high pH condition some ammonia nitrogen will be lost through volatilization (Equation 6.1 and Figure 6.9). Ammonia nitrogen is readily absorbed by soil but nitrate nitrogen is not. Nitrates that are not uptaken by the plants and not biologically denitrified (or converted into gaseous nitrogen) may be leached into groundwater.

The following example shows a method to calculate sludge application rate in the first year based on nitrogen uptake rate of a crop and considering mass balance of nitrogen in soil.

Table 9.14 Mineralization rates for organic N in wastewater sludge (U.S. EPA 1983)

Year of sludge application	Mineralization rate %		
	Raw sludge	Anaerobically digested sludge	Composted sludge
First	40	20	10
Second	20	10	5
Third	10	5	3
Fourth	5	3	3
Fifth	3	3	3
Sixth	3	3	3
Seventh	3	3	3
Eighth	3	3	3
Ninth	3	3	3
Tenth	3	3	3

Example 9.1

If corn is to be grown in a sandy loam soil, estimate the application rate of a digested sludge which has the following nitrogen analysis: organic N = 20,000 mg/L, ammonia N = 1,500 mg/L, nitrite N = 5 mg/L, nitrate N = 50 mg/L. This sludge contains 21,555 mg/L total N or 2.15% N by weight.

The annual nitrogen uptake rate for corn is about 224 kg/ha. Assume the nitrogen mineralized during the first year is 20% of the organic nitrogen and that the volatilized fraction is 50% of the ammonia nitrogen. Also assume that no N flows into the groundwater, no denitrification occur, and initial available nitrogen content of the soil is negligible.

The mass balance is:

N applied = N volatilized + N leached to groundwater + N used by plants + N lost through denitrification. (9.1)

The amount of N applied is calculated as kg/ha. N is volatilized in the form of ammonia nitrogen. Since 20% of the organic is mineralized (to ammonia), the total available ammonia N is 1,500 + 0.2 (20,000) = 5,500 mg/L, and the volatilized ammonia is 0.5 (5,500) = 2,750 mg/L (or about 0.275% N is lost through volatilization). If the annual application rate of sludge is X kg/ha dry weight, the total N volatilized is 2.75×10^{-3} (X) kg/ha.

The amount of N loss to groundwater and due to denitrification is zero. The amount N used by the corn is 224 kg/(ha-year).

The total N applied is the product of dry solids application rate, X kg/ha times the fraction of total nitrogen or 21.555×10^{-3} (X) kg/ha.

From the mass balance equation (Equation 9.1)
21.555×10^{-3} (X) = 2.75×10^{-3} (X) + 0 + 224 + 0
and X = 11,912 kg/ha
The amount of sludge to be applied to corn crop in the first year is 11,912 kg/ha (dry weight).

9.3.2 Sludge loading determination

The calculation for sludge loading on a nitrogen basis is a three-step procedure:

1. Determine the plant-available nitrogen (N_p) in the sludge during the application year:

$$N_p = (1{,}000)\,[NO_3 + K_v\,(NH_4) + f_1\,(ON)] \tag{9.2}$$

Where,
N_p = plant-available nitrogen in sludge during application year, kg/dry ton of sludge
NO_3 = percent nitrate in sludge, as a decimal (e.g. 1000 mg/L = 0.1% = 0.001)
K_v = volatilization factor: 0.5 for surface applied liquid sludge, 1.0 for incorporated (or injected) liquid sludge and dewatered digested sludge applied in any manner
NH_4 = percent ammonia nitrogen in sludge, as a decimal
f_1 = mineralization factor for first year, as a decimal (Table 9.14)
ON = percent organic nitrogen in sludge, as a decimal

Equation 9.2 will determine the plant-available N in sludge in kg/ton. To convert the concentrations of NO_3, NH_4 and ON into the same unit, the value of each of these N constituents has to be in decimal term. For example, an NH_4 concentration of 1000 mg/L is equivalent to 0.1%, or sludge 100 kg contains NH_4 0.1 kg. Therefore, sludge 1000 kg (or 1 ton) will contain NH_4 = 1000. (0.1/100). The term in bracket is the decimal value.

2. Determine the plant-available nitrogen (N_{PR}) from mineralization of the residual sludge in subsequent years:

$$N_{PR1} = 1{,}000\,[f_2\,(ON)_2 + f_3\,(ON)_3 + ...] \tag{9.3}$$

Where,
N_{PR1} = plant-available nitrogen from mineralization of the first-year sludge in subsequent years, kg/dry ton of sludge

f = mineralization rate (Table 9.14), as a decimal. Subscripts refer to the year of concern

ON = percent organic nitrogen remaining in the sludge in a particular year, as a decimal. Subscripts refer to the year of concern.

A system with continuous annual applications will have to solve Equation 9.3 for each of the subsequent year, i.e.: N_{PR2}, N_{PR3}, N_{PR4} etc. The calculations will converge on a relatively constant value after 5 to 6 years if the sludge composition remains the same.

3. The annual sludge loading (S_{Ny}) based on nitrogen is determined with:

$$S_{Nt} = \frac{U_n}{(N_P + N_{PR1......})} \tag{9.4}$$

Where:

S_{Nt} = annual sludge loading in year (t) of concern, dry ton/ha

U_n = crop uptake of N kg/(ha-year)

N_P, N_{PR1} = from Equations 9.2 and 9.3

In addition to the above three-step procedure, attention should be given to possible loss of sludge or nutrients due to surface run-off. This sludge loss can be significant in areas having high rainfall intensity and soil erosion. According to Battele Memorial Institute (1987), the extent of sludge loss is dependent upon rainfall intensity, soil erosivity, soil slope, type of crops being grown, and erosion control practice implemented at the site. Under conditions where high rainfall and steep slope prevail or when sludge application is conducting during flooding and raining, the magnitude of sludge loss due to surface runoff should be taken into consideration.

Example 9.2

Determine land area for application of anaerobically digested municipal sludge with the following conditions:

a) Sludge production: 22 dry tons/day
b) Sludge characteristics: Pb = 500 ppm, Cd = 50 ppm, Ni = 100 ppm, Cu = 500 ppm, Zn = 2,000 ppm, Total N = 2.5%, NH_4 = 1.0%, NO_3 = 0.

c) Sludge will be incorporated, so $K_v = 1$, CEC of 10 meq/100 g for site soils. Corn is the intended crop, $U_n = 180$ kg/(ha-yr).
d) The design can be based on N fertilization rates or heavy metal loading rates.

Mineralization rates (Table 9.14) for digested sludge are:

Year	f
1	0.20
2	0.10
3	0.05
4-10	0.03

Solution:

(1) Organic nitrogen (ON) = Total N – NH_4
= 2.5 - 1 = 1.5% = 0.015

From Equation 9.2, available nitrogen in the first year:

N_p = (1,000)[0 + 1(0.01) + 0.20(0.015)]
= 13 kg/ton of dry sludge

a. From the first-year sludge, the organic N remaining in second year:

ON_2 = (0.015) - (0.20)(0.015)
= 0.012

b. From Equation 9.3, the amount of first-year sludge mineralized in second year:

N_{PR2} = (1,000) (f_2)(ON_2) = (1,000)(0.1)(0.012)
= 1.2 kg/ton of dry sludge

c. From the first-year sludge, organic N remaining in third year:

ON_3 = (0.012) - (0.1)(0.012) = 0.0108

Mineralization of the first-year sludge in third year:

N_{PR3} = (1,000)(f_3) (ON_3) = (0.05)(0.0108)(1,000)
= 0.54 kg/ton of dry sludge

d. In the fourth year:

ON_4 = (0.0108) - (0.05)(0.0108) = 0.0103
N_{PR4} = (1,000)(f_4)(ON_4) = (1,000)(0.03)(0.0103)
= 0.309 kg/ton of dry sludge

e. The N_{PR} for year 5 and beyond converges on a value of about 0.3 kg/ton of dry sludge

(2) Repeat the calculations for sludge applied in years 2 through 5 and tabulate results.

a. For all applications of sludge in each year.

Year after Application	N_{PR} kg/ton
2	1.2
3	0.55
4	0.31
5	0.3

b. The total available N for each year in kg/ton will therefore increase yearly as shown in column 2 of Table 9.15. Since the crop uptake of N is fixed at 180 kg/(ha-year), the amount of sludge applied has to be decreased yearly according to Equation. 9.4, as shown in column 3 in Table 9.15.

(3) Since Cd application rate to crop should not exceed 0.5 kg/(ha-year), for this sludge containing 50 ppm Cd, the recommended loading is:

$$\frac{0.5\text{kg}}{\text{ha-year}} \cdot \frac{1}{0.00005} \cdot \frac{\text{ton}}{(1000\text{ kg})} = 10 \text{ tons/(ha-year)}$$

This Cd-application is lower than the N-application rate. Thus the sludge loading of 10 tons / (ha-year) is the LDP to be used in determining the land requirement of sludge application.

Table 9.15 Total available N and sludge application rates for Example 9.2

Year	**Total Available N (kg/dry ton of sludge)**	**Annual sludge loading (Equation 9.4), S_{Nt}, dry ton sludge/(ha-yr)**
1	13 = 13	13.85
2	13+1.2 = 14.2	12.68
3	13+1.2+0.55 = 14.75	12.21
4	13+1.2+0.55+0.3 = 15.05	11.96
5	13+1.2+0.55+0.3+0.3 = 15.35	11.73
6	13+1.2+0.55+0.3+0.3+0.3 = 15.65	11.50
7	13+1.2+0.55+0.3+0.3+0.3+0.3 = 15.95	11.28
8	13+1.2+0.55+0.3+0.3+0.3+0.3+0.3 = 16.25	11.08
9	13+1.2+0.55+0.3+0.3+0.3+0.3+0.3+0.3 = 16.55	10.88
10	3+1.2+0.55+0.3+0.3+0.3+0.3+0.3+0.3+0.3=16.85	10.68

Note: If the Cd loading rate of 1.9 kg/(ha-year) as listed in Table 9.11 is used, the sludge loading rate would be 38 tons/(ha-year). However, to avoid excessive N loading to corn crops, the land area requirements should be calculated from the sludge loading rates given in Table 9.15

(4) In case where Cd is LDP, the land area requirement for the sludge production rate of 22 tons/day is:

$$\frac{(22 \text{ tons/day})\ (365 \text{ days/year})}{10 \text{ tons / (ha-year)}}$$

= 800 ha.

(5) At the sludge application rate of 10 tons/(ha-year), Cd content in sludge = 50 ppm, and soil CEC of 10 meq/100 g, the life period of sludge application that will not allow Cd to exceed the cumulative limit as given in Table 9.10 is:

$$\frac{10 \text{ kg/ha}}{10 \text{ tons / (ha-year)}} \cdot \frac{\text{ton}}{1000 \text{ kg}} \cdot \frac{1}{(0.00005)} = 20 \text{ years}$$

The design period of this land application site based on cumulative limit of Cd loading is 20 years. The design period based on cumulative limits of other heavy metals will be several times higher than that of Cd for this type of sludge.

9.3.3 Monitoring program

Since the design is normally based on limiting both N and Cd, monitoring for these two parameters should not be necessary. Routine soil testing every 2 to 4 years for plant available P and K and to determine lime requirements for pH maintenance at 6.5 is all that should be necessary.

The schedule for sludge applications will depend on the type of crop and on the climate for the area. Sludge is not usually applied when the ground is flooded or frozen to reduce risk of runoff contamination. Sludge can be applied to the fields for row crops prior to planting and after harvest. Sludge application to forage grasses is possible in all months of the year when the ground is not flooded.

Periodic sludge analyses are needed to provide nutrient and heavy metal concentrations so that rates of application can be determined to meet crop nutrient needs, and total heavy metal loadings can be recorded from year to year.

9.3.4 Case studies

The followings are two case studies of agricultural application of sludge in the U.S.A and Canada.

Case study I: U.S.A

The city of Salem, Oregon, generates 121,120 m^3/year of anaerobically digested sludge containing 2.7 percent solids, and 90 – 95 percent of this sludge is recycled to local farmland (U.S.EPA 1984). Typical sludge characteristics after digestion are shown in Table 9.16. The sludge N levels are raised by the addition of ammonia during the treatment processes because the raw sewage contains a high percentage of food processing waste, which are deficient in nutrients. The sludge is applied to about 1,200 ha of local agricultural land. At virtually all application sites, the sludge is applied only once per year. Sludge application rates are based on the N needs of the crop and the nutrient content of the sludge. They vary from 2.2 to 6.3 dry tons/ha, averaging approximately 3.4 dry tons/ha.

The sludge is applied primarily to fields used to produce grains. Sludge-amended sites are also used to produce seed crops, Christmas tree farms, commercial nurseries, and filbert orchards. No sludge is applied to fruit and vegetable crops. For poorly drained soils, sludge can be applied from April to October. For well-drained soils, sludge can be applied anytime except during or immediately after rainstorms. Schedules for application of sludge to soils with intermediate drainage capacity fall between these two extremes. Cation exchange capacity is used to limit cumulative metal loadings added by sludge application. However, if soil pH is less than 6.5, as it is in most of the Salem area, then cumulative Cd addition is limited to 4 kg/ha, regardless of soil cation exchange capacity. As the sludge generated by Salem is very low in metals, application sites generally have a life well over 25 years.

Table 9.16 Typical characteristics of digested sludge at Salem, Oregon (U.S.EPA 1984)[a]

Characteristics	Concentration
pH	7.3
Total solids (%)	2.5
Total Nitrogen (%)	10.3
Ammonium Nitrogen (%)	5.9
Phosphorus (%)	2.0
Potassium (%)	0.96
Zinc (%)	980
Copper (mg/kg)	470
Nickel (mg/kg)	43
Cadmium (mg/kg)	7
Lead (mg/kg)	230
Chromium (mg/kg)	60
Magnesium (mg/kg)	200
Calcium (mg/kg)	12,200
Sodium (mg/kg)	3,000

[a] All constituents except pH are reported on a dry-weight.

Each sludge site is investigated by the Oregon Department of Environmental Quality, which makes recommendations on a case-by-case basis. General guidelines for sludge application sites are as follows:

1. Minimum distance to domestic wells = 61 m
2. Minimum distance to surface water = 15 m
3. Minimum rooting depth (effective depth of soils) = 0.61 m
4. Minimum depth to groundwater at time that sludge is applied = 1.22 m
5. Minimum distance of sludge application to public access areas varies with the method of sludge application:
    a. If the sludge is incorporated into soil = 0
    b. If the sludge is not incorporated into soil = 30.5 m
    c. If the sludge is pressure-sprayed (‘big gun’-type sprayer) over the soil = 91 – 152 m
6. Sludge application is not approved close to residential developments, schools, parks, and similar areas.

7. Minimum slope is largely left to the investigator's discretion. Where no surface waters are endangered slopes as high as 30 percent have been approved. Generally, however, the maximum allowable slope is 12 percent and, in cases where sensitive waters are nearby, maximum slopes may be held at 7 percent or less.

In general, pasture and grassland receive sludge applications during the winter months; agricultural land growing seasonal crops receives sludge during the warmer months, before planting or after harvesting. When weather prevents sludge application, the sludge is stored in lagoons at the treatment plant.

Sludge is usually applied by haul trucks. If the application soil is too wet or otherwise unsuitable for direct truck access, then the sludge is sprayed on to the application site.

Analyses of the sludge-amended soil showed virtually no change in soil chemical and physical characteristics. Groundwater from wells on or within 150 m of sludge application sites was sampled and analyzed before and after application. Results showed no significant changes in groundwater quality over a period of 3 years and now only selected wells are sampled approximately every 3 years. Crop tissue sampling and analysis during the initial years of the sludge application showed no significant difference between crops grown in sludge amended soils and control crops.

Case study II: Canada

The Halton region in Ontario Province operates seven municipal wastewater treatment plants treating over 220,000 m^3/day of wastewater. The primarily treated sludge is stabilized in anaerobic digesters and the stabilized sludge, rich in N, P and organic matter, is produced at about 220,000 m^3/year.

The sludge is applied on farmland (growing field crops, e.g. wheat) by tractors equipped with the injectors for direct incorporation of sludge into the ground. Another mode of sludge application by pressure spread on the field surface is also employed. At the Halton Region, sludge application rate is based on NH_3 and NO_3^- N loading which should not exceed 135 kg/ha during the 5-year period; this practice also results in about 220 kg/year of P applied on the farmland in 5 years, a cost-saving for N and P for the farmers.

According to the Ontario Ministry of Agriculture and Food (1993), the application of this sludge on the farmland follows the provincial guidelines for sewage sludge utilization on agricultural lands, and has proven to be safe. Sludge is routinely analyzed for N, P, and heavy metal contents, and strict control is maintained to prevent heavy metal overloading to the soils.

During wet weather, which could cause soil compaction and run-off problems, the sludge is taken to a temporary storage site with a sludge storage capacity of 63,000 m^3.

9.4 TOXIC SUBSTANCES VS CROP GROWTH

Toxic substances in sludge can be categorized as heavy metals and toxic organic compounds. The U.S.EPA had collected sludge samples from more than 200 representative wastewater treatment facilities and analyzed for more than 400 pollutants. They found that many toxic compounds traditionally subject to regulations were either not present or were present at levels that would not pose a health or environmental risk (Walsh 1995). Hence, only the heavy metal limits (see Table 9.11) and faecal coliform standards, reported in section 9.3 are being emphasized.

Some of the factors affecting plant uptake of heavy metals are as follows (Bitton *et al.* 1980):

1. Levels of toxic elements in the wastewater or sludge and their characteristics;
2. Species of plants grown, their age, condition, and rooting depth. Some plants are known to be metal accumulators.
3. Background concentration of toxic elements in the soil and their distribution;
4. Ability of soil chemical constituents to convert toxic elements to non-available chemical compounds. This ability is in turn affected by the nature of toxic element and the type of soil, for example:
    a. pH of the soil solution
    b. Organic and clay content and type of the soil
    c. Phosphate level in the soil
    d. Cation exchange capacity (CEC) of the soil
    e. Adsorption and precipitation.

The above factors determine the deleterious effect of heavy metals and other substances on plants and soils. In soils with high pH, most heavy metals occur in precipitated, unavailable forms. Similarly, the phosphorus uptake by plants is also retarded at high pH. Thus, calcareous solids are generally less amenable to manifestations of heavy metal toxicity than are the neutral or acidic soils.

More serious consideration is being given at present to the fate of cadmium, mercury, selenium, molybdenum, arsenic, copper, and zinc in the food chain. The other heavy metals do not seem to accumulate in edible portions of crops and are essentially phyto-toxins (some substances in trace amounts may, in fact, be advantageous for crop growth). Zinc is more readily absorbed than most other heavy metals. The presence of copper somewhat inhibits zinc transport through the plant.

There is some uncertainty at the present time concerning safe levels of many elements accumulating in plants. Little is known concerning the long-range effects of toxic elements applied to agricultural lands through the continuous use of wastewater and sludge. The guidelines given in Tables 9.10-9.13 have been proposed to minimize the health impact resulting from the heavy metals present in sludge. These guidelines should be followed wherever possible in the design and operation of land treatment of sludge. At present, polychlorinated biphenyls (PCBs) are the only group of toxic organic compounds addressed in the joint U.S. EPA/FDA/U.S.DA guidelines for sludge application for fruit and vegetable production (Table 9.12). Sludge containing more than 10 mg PCB/kg must be soil incorporated, and sludges containing more than 50 PCB/kg may not be land applied at any rate, not mixed with less contaminated sludges to lower the mixture's PCB content (O'Conner *et al.* 1990).

The principal problem arising from PCBs is direct ingestion by animals grazing on forages treated with surface-applied sludge. Dairy cattle are most susceptible to PCB contamination of forages, because PCBs in the diet are readily partitioned into milk fat. Several studies have shown that essentially PCBs do not adsorb onto the surface of root crops such as carrots, hence they are not a major concern for this kind of crops (U.S. EPA 1983)

9.5 MICROBIOLOGICAL ASPECTS OF SLUDGE APPLICATION ON LAND

With the practice of land disposal of sludge becoming more popular and widespread, the survival of pathogenic organisms in the soil, water, and on crops grown in sludge assumes increasing importance. Pathogens in soil are destroyed by the natural environmental conditions that favor native soil organisms. Some pathogens are entrapped and adsorbed at the soil surface and undergoing rapid die-off in the soil matrix.

In general, microorganisms may survive in the soil for a period varying from a few hours to several months, depending on the type of factors such as: (1) type of organism; (2) temperature: lower temperature increases survival time; (3) moisture: longevity is greater in moistened soils than in dry soils; (4) type of soil: neutral pH, high-moisture-holding soils favor survival; (5) organic matter: the type and amount of organic matter present may serve as a food or energy to sustain the microorganisms; and (6) the presence of other micro-organisms can have an antagonistic effect on the pathogens. Pathogens do not generally survive as long on vegetation as they do in soil because they are exposed to adverse environmental conditions like UV radiation, desiccation, and temperature extremes (see Figures 8.13 and 8.14).

There are various forces acting to retain or facilitate the movement of microorganisms through soil. Filtration by the soil at the soil-water interface is the primary means of retaining bacteria in the soil, or in some cases in an additional biological mat formed in the top 0.5 cm of soil. Other mechanisms that retain bacteria in the top few cm of fine soil are intergrain contacts, sedimentation and adsorption by soil particles. The soils containing clay remove most microorganisms through adsorption, while soils containing sand remove them through filtration at the soil-water interface. The movement of microorganisms through soil relates directly to the hydraulic infiltration rate and inversely to the size of soil particles and the concentration of cations in the solute. Microorganisms will travel quickly through fissured zones, such as limestone, to the groundwater.

The potential for pathogen transmission exists and can cause a public health problem if land application is carried out improperly. The transmission can occur through groundwater, surface runoff, aerosols formed during application and direct contact with the sludge or raw crops from the application site, because bacteria, viruses and parasites do not enter plant tissue, transmittal of pathogens via crops grown on the land application site results from contamination of the plant surface. If contaminated crops are consumed raw, disease transmission is possible; however, disease transmission due to application of sludge onto farmland is rare. Reported outbreaks of disease generally have been the result of application of inadequately treated sludge to gardens or other crops which were eaten raw.

Pathogens in land-applied sludge usually will die rapidly depending on temperature, moisture and exposure to sunlight. In general, pathogen survival is shorter on plant surfaces than in the soil. To prevent disease transmission, sludge should not be applied to land during a year when crops are to be grown that will be eaten. Where humans have little physical contact, the presence of pathogens may be of less concern. The soil can filter and inactivate bacteria and viruses. Sludge application methods and rates should take advantage of the soil to reduce public health concerns.

The microorganisms present in human/animal wastes and in sludge as described in Chapter 2 can pose potential health risks when these wastes are applied on land and agricultural crops. From a review of epidemiological effects of the use of sludge on land, the transmissions of hookworm, *Ascaris*, *Trichuris* and *Schistosoma japonicum* infections should be of major concern (Blum and Feachem 1985). The above helminths are present in ova form in sludge, hence their long survival in soil or on crops and becoming high risks to human health (see Table 2.26). In general, the microbiological guidelines as given in Table 2.27 should be followed to minimize this public health impact.

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9.7 EXERCISES

9.1 Discuss the advantages and limitations of agricultural utilization of sludge, and compare them with aquacultural utilization (or fish production) of sludge.

9.2 Why is it important to maintain the soil pH at 6.5 or greater in sludge application on land? What should be done if the land for sludge application has a pH lower than 6.5?

9.3 Objectionable odour of the sludge could result in unfavourable public relations and reduced acceptance of land application options. Therefore, all sludge management systems must consider objectionable odour as a potential problem. What measures should be taken to reduce the odour problems during sludge application on land?

9.4 A piece of land received anaerobically digested sludge containing 3 percent organic N at a rate of 15 dry tons/ha in 2003. In 2004, a composted sludge containing 2% organic N was applied to the same land at a rate of 10 dry tons/ha. Determine the available N in the Year 2005 from the sludge applications in the year 2003 and 2004.

9.5 An analysis of a composted sludge reveals the following information:

Production	100 tons/day
Dry solids	15 %
Total N	3.5 %
NO_3-N	0.1 %
NH_4-N	1.6 %
P	1.2 %
K	0.3 %
Zn	2000 ppm
Cu	1000 ppm
Ni	100 ppm
Cd	2 ppm
Pb	500 ppm

Determine the land area needed for application of this sludge for a period of ten years and the amount of additional chemical fertilizers required. The sludge is to be incorporated into cotton fields with a CEC of 8 meq/100 g soil. Nutrient uptake rates of cotton are given in Table 8.7.

9.6 The Chiang Mai Municipality in northern Thailand produces septage (or anaerobically digested sludge) with the following characteristics:

Total weight	= 100 tons/day
Total solids (TS)	= 15 tons/day
Organic N	= 20,000 mg/kg of TS
Cd	= 20 mg/kg TS

The septage is to be applied by incorporation into a land for growing soya bean, whose N uptake rate is 250 kg/(ha-year). Assuming N loss via volatilization and runoff is negligible.

a) If all the septage is to be used to grow soya bean, based on N requirement alone, determine the land areas for growing soya bean in years 1 and 2. Data on N mineralization rate is given in Table 9.14.
b) If the Cadmium application rate to the soya bean field should not exceed 0.5 kg/(ha-year), determine the land areas, based on Cd limit alone, for growing soya bean in years 1 and 2.

Compare the results of a) and b) and recommend to the Chiang Mai Municipality the best option for applying septage to grow soya bean.

9.7 A cattle farm in southern China produces animal manure (raw sludge) with the following characteristics;

Total weight	= 2 tons/day
Total solids (TS)	= 0.2 tons/day
Organic N	= 20,000 mg/kg TS
Arsenic (As)	= 10 mg/kg TS
1,000 kg	= 1 ton

This animal manure is to be applied as fertilizer to grow sunflower crops whose N uptake rate is 200 kg/(ha-year). Assume N losses via volatilization and runoff is negligible.

a) If the farmer has only 1 ha of farm land to grow sunflower crops, determine the amounts of animal manure the farmer should apply to this farm land in years 1 and 2 to obtain maximum crop yields and minimum impact on the environment. Data on N mineralization is given in Table 9.14.

b) Table 9.11 shows the land application pollution limits of various heavy metals, including *As*. Based on *As* limits alone, determine if this animal manure is suitable to be used as fertilizer for sunflower crops or not? If yes, determine the annual amount of animal manure that can be applied on this 1-ha farmland and the life period of this farmland that can be used for sunflower cultivation until the *As* cumulative loading limit is reached.

9.8 Discuss the significance of CEC in sludge application an agricultural land. You are to determine CEC of soil in your hometown and evaluate the feasibility of applying municipal or agricultural sludge to agricultural land in your hometown.

9.9 You are to conduct an opinion survey on social acceptance of agricultural products fertilized with sludge from domestic, agricultural or industrial sources and recommend measures to increase public acceptance.

10

Management of organic waste recycling program

This chapter describes the management procedure for organic waste recycling program. A waste management program should include as many alternatives as possible to enable the decision making process to reach a cost-effect solution. A sequential approach in the management of an organic waste recycling program generally comprises of: planning, technology and site selection including cost benefit analysis, institutional arrangement, compliance with regulatory guidelines and standards, and monitoring and control of facility performance. Each of these aspects and some case studies are presented below.

10.1 PLANNING FOR WASTE RECYCLING PROGRAMS

Waste recycling program has been practiced in many countries for decades, but proper planning procedures and institutional set-up are yet to be developed. The overall success of a waste-recycling program depends greatly on its planning and implementation.

Planning for a waste-recycling program requires the following aspects for consideration.

1. Raw materials: Wastes from households, industries and public institutions are the ingredients of a waste recycling program and the outcome is the useful products as well as other benefits, such as public health improvement and pollution abatement. The program has to envisage the limitation of the waste quality and quantity over the planning period.
2. Manpower: Various levels of skill are needed for the execution of the program. Present and future requirements of manpower are to be estimated, and future development of manpower planned.
3. Capital: A waste recycling program or project has to be financially viable. It may be necessary to initially fund the programs by local authorities or by international agencies. Later on, collection of fees for waste collection and treatment and sale of the recycled products have to be implemented which should be satisfactorily accepted by the public.
4. Technology: Collection, handling, processing and final disposal/reuse of the waste and by-products need efficient methods so as to maximise the benefits and minimise the environmental pollution.
5. Market study: all the resources and effort devoted to recover and recycle the wastes will not be useful if there is not market for the recycled products. Waste recycling technology and facilities must be able to consistently meet the user's quality, quantity and reliable delivery period, when required.
6. Political will: This is an important aspect of a waste-recycling program. Education of the people at all levels to promote public awareness and to realise the importance of waste recycling has to be done continuously. Uncertainties and myths have to be clarified, such as the aspects of public health and environmental impacts due to waste recycling programs.

The above-mentioned aspects inter-relate and influence each other with respect to a decision to proceed with a waste recycling program. In general, steps that should be considered in the planning of waste recycling program (Figure 10.1) are:

1. Identification of objectives
2. Constraints
3. Data collection
4. Analysis of principal options
5. The decisions and process of review

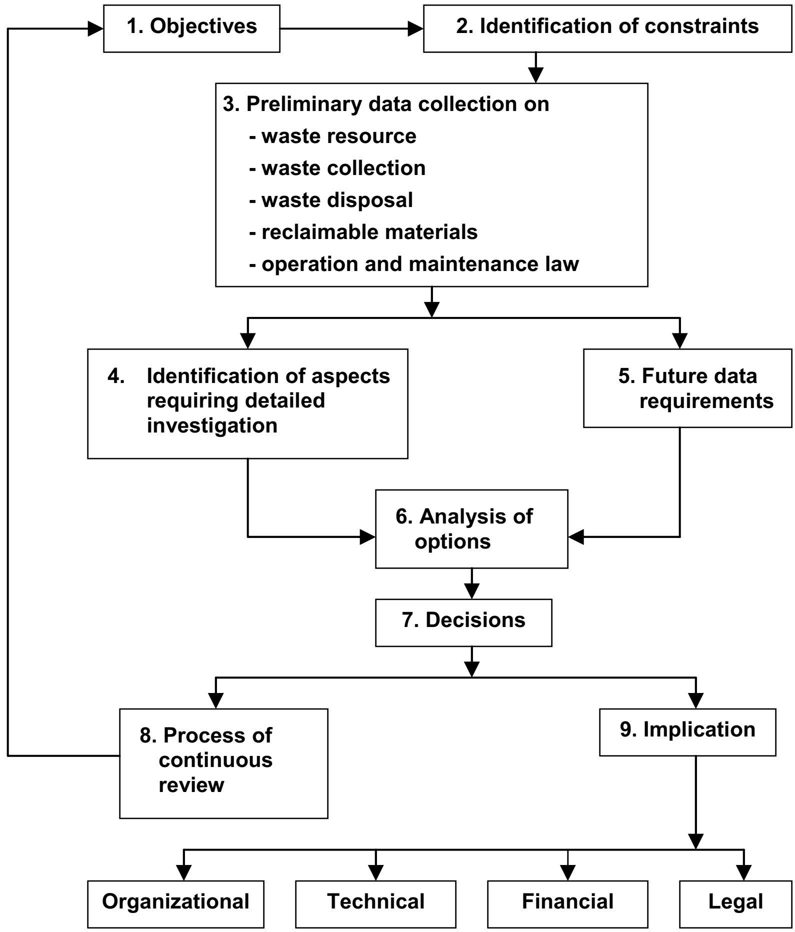

Figure 10.1 Principal steps in the development of a waste-recycling program (Thanh *et al.* 1979)

10.1.1 Identification of objectives

The objectives should identify the purpose of the waste recycling program, that is to be able to reclaim, reuse and at the same time to treat the waste to a certain degree that it does not cause health hazard or environmental pollution. In considering the cost effectiveness of a waste-recycling scheme, the benefits to be gained from pollution control and public health improvement should also be taken into account.

The objectives should, in particular, include what the plan is to encompass in terms of:

1. geographical area, where waste collection and treatment/recycling can be planned on a regional basis to minimize expenditures and to yield effective management of the system;
2. types of waste, so that appropriate waste recycling program can be selected;
3. time period of the plan, which depends on local circumstances and needs such as the waste quantity and characteristics and long-term needs of the recycled products.

10.1.2 Constraints

There are a number of constraints that will tend to limit the available waste recycling alternatives. By recognizing these at the outlet, a great deal of unnecessary work can be avoided; their recognition will also be of assistance in the eventual selection of appropriate recycling scheme. These constraints are:

1. Financial constraints, which may limit the use of capital-intensive high technology for recycling the waste, unless the advantages or market for the recycled products are promising. For example, it may not be appropriate to employ a Dano composting unit (Figure 3.18) to produce compost fertilizer where farmers still prefer to use chemical fertilizers available cheaply. In addition, the production of virgin materials often enjoys a wide range of subsidies and incentives that make them cheaper then the recycled products.
2. Manpower constraints; the manpower constraint in the planning of waste recycling program should be taken into account such as the need for skilled technicians to operate some biogas digesters and high-rate algal ponds.
3. Land use constraints; some waste recycling systems are not suitable for urban and suburban areas due to shortage of land. Existing land uses will provide the best guideline that is likely to prove more or less acceptable.
4. Environmental constraints; hydrogeological characteristics of the waste recycling area must be considered so that the environment of the site and nearby is not affected by this practice.
5. Public acceptance constraints; the recycled products from the waste recycling processes should be acceptable to the public, otherwise the recycling process is of no use. In general, people do not want to have waste recycling sites located close to residential areas.

10.1.3 Data collection

Preliminary information requirement

The following information will be required for the planning of waste recycling program:

1. population, housing, industries, or agricultural activities;
2. waste quantity, composition and source;
3. waste storage, collection and transportation;
4. treatment and disposal/reuse methods; existing methods, future capacities, plant's life, local hydrogeology, land availability;
5. existing waste recycling system and benefits achieved, if any;
6. public acceptance of reclaimed products
7. management and law, organization, regulations and their enforcements.

Detailed investigation

In particular, there is often a shortage of information on the quantity and composition of waste, and the amount of reclaimed products. Hence, detailed surveying and estimating the quantity and composition of waste should be carried out before planning a waste-recycling program.

Both waste quantity and composition are subject to daily and seasonal fluctuation. Waste recycling facilities must be provided to cope with peak waste load rather than the average, and seasonal variations in the quantities of available materials may have impact upon the extent of resources recovery. In addition, data on national average characteristics of the wastes can be significantly different from local characteristics of the wastes of concern.

For the treatment and recovery of products (e.g. composting - material recovery; anaerobic digestion - energy and materials; pond system - food production), the waste composition is an important factor.

Where specific problems have been identified, a more detailed investigation on waste composition and quantity will be required to provide sufficient data for the options or decisions to be made. The detailed investigations should also take into account the amount and value of reclaimed products as well as their public acceptance. Long-term outlets for these reclaimed products should also be considered.

10.1.4 Analysis and decisions

Where a number of options for waste recycling scheme are available, it is necessary to evaluate each option for capital and operating costs, the benefits and associated health and environmental impacts.

Alternative technological options and waste recycling plans are assessed against a set of criteria which will normally encompasses economic, technical, environmental and political objectives. Possible subdivisions of each category are suggested in Table 10.1. The selection and definition of criteria are dynamics, with feedback occurring from later stages of the planning process. For example, the criteria may be revised or the emphasis given to a particular criterion may be altered when practical implications rather than initial abstractions are considered.

With regard to cost and benefits, all elements in the systems should be costed for comparisons on the options and for evaluation of improvements in performance. Costs and benefits should be expressed in terms of cost and benefit per ton of waste recycled in the system. The costs include capital and operating cost in terms of its present value whereas the benefits should include not only in terms of financial benefits but also its pollution control and public health impacts.

Table 10.1 Criteria for the assessment of waste recycling plans (Wilson 1981). Reproduced by permission of Oxford University Press

Economic
Capital costs
Land costs
Operating costs
Revenues:
Extent of market commitment
Stability of markets
Net recycling cost per ton of wastes
Net present cost of the recycled products
Sensitivity of costs to market or other fluctuations
Uncertainty in cost estimates, i.e. financial risk
Technical
Adequacy of the technology:
Feasibility
Operating experience
Adaptability to local conditions
Reliability
Interdependence of components (can the system be operated if one component fails?)

Table 10.1 Criteria for the assessment of waste recycling plans (Wilson 1981). Reproduced by permission of Oxford University Press (continued)

Safety
Potential for future development
Flexibility to cope with changes in:
Waste quantities
Waste composition
Source separation of materials
Dependence on outside systems:
e.g. vulnerability
Environmental
Public health
Water pollution
Air pollution:
Dust
Noxious gases
Odors
Quality and quantity of residual wastes
Noise
Traffic
Aesthetics
Political
Equity between communities or interest groups
Flexibility in location of facilities
Public acceptance
Number of jobs created
Employee acceptance
Use and conservation of resource
Products covered:
Market potential
Net effect on primary energy supply:
Energy requirements
Net effect on supply of materials:
Raw materials usage
Land usage:
Volume reduction
Land reduction
Water requirement

10.2 GUIDELINES FOR TECHNOLOGY AND SITE SELECTION

10.2.1 Definition of technology and its choice

Technology is often identified as knowledge about machine and processes, extending to skill, knowledge and procedures for making, using and doing useful things. It includes the nature and specification of what is produced as well as how it is produced. A complete description of technology used in a country must include the organization of productive units in terms of scale and ownership.

10.2.2 Limiting factors in the choice of technology

In general, people would select a technology that is suitable to its environment and economical to operate. However, technology selection is not an easy job. There are some factors that limit the choice of technology. The first factor is the incomplete knowledge of the techniques and methods. Technology is generally developed in industrialized countries. Although in some instances a certain technology can be adapted to developing country environment, no country is willing to try it because of the lack of knowledge of that technology. The absence of individuals or group involved in using the technology in the community also hinders technology selection. This is true when the individual or the community lacks the entrepreneurial spirit to innovate or try new. Unless the technologies from other countries are tried and tested, the choice of technology selection would be very limited.

Guidelines for technology selection are proposed to possibly reduce the failures in adopting technology from other countries. Although some techniques like the use of excreta for composting are acceptable in some region, they may not be socially acceptable in other countries. The following guidelines are recommended for the technology selection in waste recycling and recovery, but should be applicable to other categories of technology also:

1. The technology should be suited to the local environment economically and culturally
2. The operation and maintenance should be easily undertaken by the local manpower;
3. The technology should use, whenever possible, local materials and energy sources. In such case that imported materials are recommended, it must be affordable and easily obtainable;
4. The technology should be simple and easily understood by the local people and have certain flexibility for possible changes;

5. The technology should be innovative in order to improve the human and material conditions of the local people through the use of new organizational types and new technological devices;
6. The technology whenever possible could be sited in existing high density areas;
7. The technology should not directly or indirectly contribute to the pollution and destruction of the existing ecology;
8. The technology should enhance the health and sanitation and upgrade the economic well being of the community.

Site identification

An ideal site to be selected for organic waste recycling program should be the one that supports the community livelihoods and is acceptable to the people. A preliminary site screening should be conducted to obtain such important data as: soil characteristics, depth to ground water, site grades, land use patterns at present and in the future and haul distance of organic wastes from the community to the potential site. To minimise health risks and gain better public acceptance, the organic waste-recycling site should be located downwind and away from the community centres.

Important information needed for site selection is the land area requirement, which is usually dependent on the required degree of waste treatment and the technology of organic waste recycling to be employed. The design criteria and procedures outlined in Chapters 3-9 can be used in determining land area requirements. For composting, no special site investigation is required but impermeable barrier should be provided to protect groundwater contamination. In general the area estimate for aquatic weeds and land treatment of wastewater depends on the effluent quality required. The requirements for these systems include: proximity to surface water for effluent discharge, impermeable soil or liner, no steep slopes, out of flood plain or dike, no bed rock or ground water within excavation depth. A suitable location must have favourable climate to support growth of aquatic plants and other biological components. For constructed wetlands, impermeable soil or liner is required to prevent the soil and ground water contamination. The constructed wetlands should be built on land having slopes 0-3% and not located in flood plain.

For slow rate land treatment systems, soil should be clay loams and sandy loams. On the other hand, sandy loams and sands are required for rapid infiltration systems. For an overland flow system, land with relatively impermeable soils, such as clay and clay loams, is necessary. The slope of the land should be in the range of 0-15%. The depth to ground water and bedrock is not critical, but it should be kept at least 0.5-1m.

Apart from the purpose of wastewater or sludge management, local knowledge, technical and cost requirements including regulatory standards should be taken into account in the selection of a suitable site for the intended organic waste-recycling program.

Site evaluation

Site evaluation involves field surveys to confirm the data obtained from the preliminary site screening. The following aspects should be undertaken during site evaluation:

1. Soil investigation: This includes determination of soil texture and structure. Soil borings should be conducted to investigate the depth of soil and groundwater table. In the design of land treatment of wastewater, information on soil aggregation is necessary to make a decision on an appropriate system.
2. Soil chemistry: The chemical properties of soil such as pH, cation exchange capacity (CEC), and sodium absorption ratio (SAR) have effects on the removal efficiency of pollutants such as heavy metals and toxic organic compounds.
3. Soil infiltration and permeability: The ability of water to infiltrate and percolate a soil is a critical factor in the design of constructed wetlands and land treatment systems. Porosity, the ratio of void to the total volume of soil, should be determined (as a decimal factor or percentage) and incorporates in the design of concerned treatment/recycling systems.
4. Buffer zone: The concept of having buffer zone is based on aesthetic and public acceptance. Organic waste recycling technologies may create an obnoxious odor and the potential for aerosol transportation of pathogens during the application of wastewater, both problems can be minimised through the application of buffer zones.

Cost and benefit analysis

The cost of an organic waste-recycling program normally includes: investment costs for land, facility construction, site preparation and associated requirement, and operation and maintenance costs. Except for the land cost, the total investment, operation, and maintenance costs of an organic waste recycling system are generally lower than those of the conventional treatment systems. In addition, the valuable by-products obtained from organic waste recycling such as compost fertilizer, biofuels and protein biomass, etc., are financial benefits to be gained from this practice. As mentioned earlier in Chapter 1, other intangible benefits such as environmental protection and health improvement resulting from organic waste recycling programs should be taken into account.

10.3 INSTITUTIONAL ARRANGEMENTS

A critical dimension in the success of waste recovery and recycling programs concerns an institutional arrangement between the government agencies, municipalities, private corporations, and non-government organizations. All these institutions must join together and coordinate all activities in order to avoid conflicts and duplication of works and duties. Institutional arrangements may be considered for financing, administering and operating recovery and recycling projects. In developing countries, without government guidance it seems unlikely that other institutions can be expected to handle waste materials efficiently and optimally. Some government control, guidance and incentive are necessary to secure success in pursuing the program. A strategy or approach has to be developed, either regional or grassroots, to lay the foundation of work. Private corporations and non-governmental organizations including international agencies and foundations should be approached for financial or technical support. The municipality must cooperate with the government for the promotion and implementation of planning programs. Cooperatives or districts should be established to be directly involved in construction, operation and maintenance of recycling facility if there are any.

The development and application of science and technology should be conducive to waste recycling from the basis of comprehensive policy of these agencies. Furthermore, policy that takes into account natural, economic and social characteristics of each region or locality, if taken wisely, would secure more cooperation in creating recycling policy.

To make steady progress in waste recycling policy to produce more satisfactory result in this direction, all parties interested in recycling issues (such as government agencies, municipality, non-profit corporation, entrepreneurs, and inhabitants), should be aware of their respective roles and make continuous efforts befitting their positions. Government agencies, among others, have the leading role to make the program successful.

Close cooperation among interested parties (including government agencies, municipality, non-profit agencies, entrepreneurs, and inhabitants) is indispensable to enforce recycling policy that take into account either local or regional characteristics. Each of the institution has to have a role. The following institutional arrangement is suggested for the success of a recycling and reuse program.

10.3.1 Government agency

Its role is to:

1. Formulate policy, prepare guidelines, and undertake planning programs on waste recovery and recycling.
2. Extend technical, financial and management support to all participants of the program.
3. Promote and coordinate all activity related to waste recovery and recycling to assure public acceptance of the program and to avoid duplication of work.
4. Monitor success and failures of the program. Formulate alternate programs to reduce losses (in terms of investment).
5. Undertake manpower development and training programs for people involved in the program.

10.3.2 Municipality

Its role is to:

1. Assist the government agencies in the selection of the most appropriate recovery and recycling programs that would be established in community.
2. Act as a link between government agencies and the community for the continuous flow of information necessary to ensure success of recovery and recycling program.
3. Initiate acceptance and participation of the people on the government program through information dissemination.
4. Assume a leading role in the formation of cooperatives or a local district, which would have a direct responsibility over the implementation of recovery and recycling program in the community.
5. Assist the cooperative and district or individual in identifying problem areas. Recommend remedial solutions to prevent failure of the program.

10.3.3 Private corporation

Its role is to:

1. Assist the government agency and municipality in waste recovery and recycling program by extending financial and possibly technical support.
2. Embark on projects that would transform their wastes into useful products, (this is possible for private corporations dealing with agro-based industry where large quantity of agro-industrial wastes are produced, see Chapter 2).

3. Undertake some research for the development of sound technology in recovery and recycling program.
4. Participate in government programs by providing loans at low interest rate to community or individual who need capital for construction of equipment and facilities needed in recovery and recycling.
5. Assist in the promotion of the programs.

10.3.4 Non-government organization

Its role is to:

1. Assist government agencies and municipalities in waste recycling and recovery programs by extending financial and technical assistance.
2. Finance projects that may have low profitability but would insure the abatement of pollution and degradation of environment.
3. Assist in the promotion of pioneer or innovative technology in waste recovery and recycling.
4. Assist the government in the manpower development and training as well as the technology transfer.
5. Undertake research for the improvement of recycling technology.

10.4 REGULATORY ASPECT

Appropriate legislation establishes binding policies and standards, provides the base for substantive and procedural regulations and creates institutions to implement policies and enforce the rules. Legislation is a measure of the public acceptance of the need for waste recycling and enhancement through institutions; it is also a measure of how adequately waste recycling institutions are entrusted with political clout and legal justifiability such that environment regulations are better enforced. Waste recycling legislation and waste recycling administration reinforce each other, and in the process become practically more effective.

10.4.1 Legislation in developed countries

It is well known that developed countries, such as the U.S.A., Japan, and Germany have paid much attention to environmental quality control for decades. Environmental legislations in these countries are very stringent and have been progressively developed for several years. Application of waste recycling technology in pollution control has been widely practiced in these countries. For example, Japan has achieved a waste-recycling rate of 55.4% (Environment Agency 1993) and the U.S.A. was expected to achieve a waste-recycling rate of

50% in the year 2000 (Grogan 1993). Table 10.2 lists water quality standards set by U.S. EPA, WHO and Japan, which together with Table 2.27 and 2.28, can be used as guidelines for setting waste recycling objectives. Table 10.3 gives some examples of measure that could be used to encourage resource recovery. Table 10.4 shows some measures employed in European Community countries for promoting reclamation. Solid waste legislations including waste recycling goals in some states of the U.S. A. are presented in Table 10.5.

10.4.2 Legislation in developing countries

One of the most difficult problems facing governments of developing countries is how to set up appropriate legislation on environmental quality control. Examples of such legislation include water quality standards, treated effluent standards for industrial and domestic wastes, ambient air quality standards, waste reuse and recycling regulation. Because setting of this legislation influences the cost of development projects (both capital and operation and maintenance costs), development of appropriate legislation requires knowledge of the receiving environment, available technology, and affordability.

UNEP (1991) reported that deaths due to infectious and parasitic diseases are six times more frequent in developing countries than in developed countries. One possible cause of the diseases is the severe degradation of water quality, which is due to less stringent water quality standards and ineffective implementation. Experiences in implementing the water quality standards in Japan reveal that actual effectiveness of a water pollution control system depends not on values of the regulated parameters, but on the supporting measure to implement the system itself.

In general, developed countries have rich experiences in waste recycling legislation, the most cited example being the Resource Conservation and Recovery Act (RCRA) of the U.S.A. On the contrary, most of the developing countries do not have any laws concerning waste recycling. Recently, however, waste recycling has been included in the national policies of some developing countries, either in the promotion stage and or in the drafting of the legislation. Therefore, investigation and evaluation of legislative instruments used in the developed countries should be made prior to formulating the legislation.

Porteous (1977) proposed the following fiscal/regulatory measures, which may be used, either singly or more likely jointly, for recycling programs:

1. resource depletion levy, which is a negative incentive applied to the producers to prevent the rapid run-down of virgin materials
2. virgin material tax, e.g. an import levy on groundwood pulp to encourage the use of a higher recycled paper content in newsprint.

3. recycled materials utilization incentives; these can be a straightforward subsidy or tax allowance for the consumers of recycled as opposed to virgin materials;
4. accelerate depreciation allowances; these would be made available to the recycling industries on plant and buildings used wholly or partly for reclamation and recycling;
5. price support, i.e. excess stocks of recycled materials are not allowed to drive down the price, thus allowing recycling efforts to continue at predetermined levels.

Other legislative instruments for regulating and promoting waste recycling programs, as listed in Tables 10.3-10.5, which are applicable to developing countries, are:

1. mandatory source separation
2. mandatory deposit-refund system
3. payment per unit of waste handled
4. advance disposal fees
5. disposal bans
6. tax credit
7. subsidies
8. market development initiatives

Each instrument has some advantages and constraints in implementations, depending on areas, economic, people, waste characteristics, public participation, and public awareness of each country. Some developed countries like U.S.A. and Japan, whose gross national products are considerably high, would have capacity of implementing monetary instruments, such as advance disposal fees, payments per unit of waste handled, and subsidies. Furthermore, people in these countries are willing to incorporate waste recycling program because the public environmental awareness is somewhat high.

To utilize effectively these legislative instruments in developing countries, the legislators should realize the realistic status of the country as well as crucial roles of the institutes/agencies involved, as previously described in section 10.3.

Table 10.2 Water quality standards of U.S. EPA, WHO, and Japan (Lohani and Evans 1993)

Parameter (Average maxima, except [ ] = minima) (ND = non-detectable)	U.S. EPA					WHO	Japan				
	CWS	RWS	FS	RC	AG	RWS	CWS	RWS	FS	RC	EF
1. Physical parameters and solids											
1.1 Temperature (°C)											
1.2 Color (units)						300					
1.3 Turbidity (units)	1	75									
1.4 Suspended solids (mg/L)							25	25-50			200
1.5 Total dissolved solids (mg/L)	500					1,500					
1.6 Dissolved oxygen (mg/L)			5.5				7.5	5-7.5			
2. Mineral water quality parameters											
2.1 Buffer capacity/pH/hardness											
2.1.1 Alkalinity ($CaCO_3$) (mg/L)			[20]								
2.1.2 pH	5-9		6.5-9.0					6.5-8.5	6.5-8.5	6.5-8.5	6.5-8.5
2.1.3 Hardness ($CaCO_3$) (mg/L)	150[b]										
2.2 Major cation (mg/L)											
2.2.1 Calcium (ca)											
2.2.2 Magnesium (Mg)											
2.2.3 Sodium (Na)	250										

Table 10.2 Water quality standards of U.S. EPA, WHO, and Japan (Lohani and Evans 1993) (continued)

Parameter (Average maxima, except [ ] = minima) (ND = non-detectable)	U.S. EPA					WHO	Japan				
	CWS	RWS	FS	RC	AG	RWS	CWS	RWS	FS	RC	EF
2.3 Minor Cation (mg/L)											
2.3.1 Sulfate (SO_4)	250										
2.3.2 Chloride (Cl)	250										
2.3.3 Nitrate (NO_3)	45		225			45					
2.4 Iron and manganese (mg/L)											
2.4.1 Iron (Fe, soluble)	0.3		1			50					
2.4.2 Manganese (Mn, soluble)	0.05					5					
3. Nutrient/eutrophication parameters											
3.1 Nitrogen (mg/L as N)											
3.1.1 Nitrate (NO_3)			80								
3.1.2 Nitrite (NO_2)			5								
3.1.3 Total nitrogen											
3.2 Phophate (mg/L as P)											
3.2.1 Total phosphate				0.025-0.005[c]							
4. Agricultural parameters											
4.1 Boron (mg/L)					0.75						
4.2 Sodium adsorption ratio (SAR)					4-8						
4.3 Total dissolved solids (mg/L)					500						

Table 10.2 Water quality standards of U.S. EPA, WHO, and Japan (Lohani and Evans 1993) (continued)

Parameter (Average maxima, except [ ] = minima) (ND = non-detectable)	U.S. EPA					WHO	Japan				
	CWS	RWS	FS	RC	AG	RWS	CWS	RWS	FS	RC	EF
5. Aquatic ecology											
5.1 Dissolved oxygen (mg/L)											
6. Recreation/swimming											
6.1Coliforms, total (no./100 mL)								50	1,000-5,000	300,000	
7. Pollution parameters											
7.1 Coliforms, total (no./100 mL)	1			1,000 126		5,000					
7.2 Coliforms, *E.coli* (no./100 mL)						6		1	2.5	2	12
7.3 BOD (mg/L)						10					
7.4 COD (mg/L)						1					
7.5 Oil/grease (mg/L)		ND		ND		0					
7.6 Floatables (mg/L)		ND		ND		0.5					
7.7 MBAS	0.5										
8. Heavy metals											
8.1 Barium (mg/L)	1										
8.2 Cadmium (mg/L)	10	10	0.7-2[d]			10	10				100
8.3 Chromium (VI) (mg/L)	0.05		0.11[d]				0.05				0.5
8.4 Chromium (total) (mg/L)	0.1	0.17				0.05					2
8.5 Copper (mg/L)	1	1	0.006-0.02[d]			1.5					3
8.6 Lead (µg/L)	50	50	1.8[d]			50	100				100

Table 10.2 Water quality standards of U.S. EPA, WHO, and Japan (Lohani and Evans 1993) (continued)

Parameter (Average maxima, except [ ] = minima) (ND = non-detectable)	U.S. EPA					WHO	Japan				
	CWS	RWS	FS	RC	AG	RWS	CWS	RWS	FS	RC	EF
8.7 Mercury (µg/L)	0.1		1.012[d]				0.5				0.5
8.8 Nickel (mg/L)	0.013	0.13	0.06-0.16[d]								
8.9 Selenium (mg/L)	0.01		0.035			0.01					
8.10 Silver (µg/L)	50		1-1.3								5
8.11Zinc (mg/L)	50		0.2-0.6								
9. Other toxics											
9.1 Ammonia (NH_3) (mg/L)											
9.2 Arsenic (mg/L)	0.05		0.19[d]			0.05	0.05				0.5
9.3 Chlorine, free (mg/L)	0.1					0.05					
9.4 Cyanide (mg/L)	0.2	0.2	0.005[d]			0.2	ND				1
9.5 Fluoride (mg/L)	1.1-2.4					1.5					15
9.6 Phenol (mg/L)	0.3		2.6			0.002					5
9.7 Sulfide (H_2S) (mg/L)											

[a] Raw water supply suitable for treatment by conventional rapid sand filtration to produce finished CWS
[b] Moderate hardness
[c] 0.025 for reservoirs, and 0.05 for steams
[d] 4-day average, once every 3 years
CWS = community water supply; RWS = raw water supply; RC = recreation (fresh/marine); AG = agriculture; FS = fishery; EF = effluent; MBAS = methylene-blue-active substances

Table 10.3 Examples of measures for encouraging resource recovery (Environmental Resources Ltd 1978)

Stage of material handling initially affected	Fiscal measures		Regulations	
	Taxes	Subsidies[a]	By legislation	By official procurement
Waste discharge	Tax on waste discharged in uncontrolled	Publicity campaign on the need for reclamation. Payments for waste	Prohibition of uncontrolled discharge	
Initial recovery	Tax on waste not recovered	Finance for data bank for information on recovery methods. Financial assistance for research and development or pilot plants, new operating plants, etc. Payments per unit of waste handled for recovery in an acceptable manner. Finance	Requirement that waste be recovered and/or particular recovery methods be used. Requirement that authorities and other organizations cooperate in various ways. Requirement that a certain level of stocks of reclaimed material be held	
Further treatment	Tax on material not subjected to further treatment		Requirement that recovered materials be treated in certain ways. Requirement for a necessary degree of cooperation between waste handlers/reclaimers and material users. Requirement that a certain level of stocks of reclaimed material be held	

Table 10.3 Examples of measures for encouraging resource recovery (Environmental Resources Ltd 1978) (continued)

Stage of material handling initially affected	Fiscal measures		Regulations	
	Taxes	Subsidies[a]	By legislation	By official procurement
Production and sale	Production charges (tax) on items contributing to waste or difficult to recover. Deposit refundable on return for reclamation. Tax on virgin materials	Publicity campaign and data bank for information on nature of reclaimed materials and products made from them. Payments in relation to use of reclaimed material (e.g. direct grants, assistance with new plants, etc.). Finance for stockpiling of reclaimed material	Requirement that products meet certain standards of recoverability and/or incorporate a certain proportion of reclaimed material. Prohibition of certain products that create non-recoverable wastes. Requirement that a certain level of stocks of reclaimed material be held	Setting of standards of recoverability and/or reclaimed material content for products purchased

[a] Including reliefs from existing taxes

Table 10.4 General measures in selected European countries for promoting reclamation (Environmental Resources Ltd 1978)

Type of measure	Country	Action
1. Procurement policies	France	Government intends to specify minimum proportions of secondary materials in products procured for public bodies
	Germany	Government intends to specify proportions of secondary materials in products procured for public bodies
2. Specifications to encourage demand for reclaimed materials	France	For categories of products defined by Government, it is forbidden to discriminate against the presence of reclaimed materials in products, which satisfy regulations and standards. Law enables Govern to fix minimum proportions of secondary materials contained in products
	Germany	Quality control and standardization of secondary materials under investigation
3. Financial assistance to reclamation projects	Belgium	Investment grants up to 60% of construction costs available to municipalities for waste treatment and recovery plants
	Denmark	Limited *ad hoc* research and development grants for private and public sector projects
	France	National Agency can make available research grants
	Germany	Grants available for innovative investments and research and development into reclamation. Grants available for plants to reclaim energy from waste

Table 10.4 General measures in selected European countries for promoting reclamation (Environmental Resources Ltd 1978) (continued)

Type of measure	Country	Action
4. Other measures to assist with separation and use of reclaimed material	Belgium	New company planned to handle reclamation from refuse
	Germany	Provision under tax law for accelerated depreciation in investments of immediate and exclusive benefit to the environment. Government is considering regulations to make recovery from certain types of waste obligatory
	Netherlands	Under proposed law, Government may order the separate collection of domestic wastes
	Italy	Law of March 1941 requires communities with over 50,000 population to segregate refuse (not in use)
5. Public education programs	France	Public education program planned
	Germany	Public education program on waste and recovery planned

Table 10.5 Solid waste legislation by some states of U.S.A. (Grogan 1993)

Date passed	WR/R[a] goal	Completion date	Product and disposal bans	Funding	Other unique characteristics
				California	
1989	25% 50%	1995 2000	None	Statewide disposal surcharge. Advance disposal fee on tires	Tax credit on purchasing of recycling equipment. Newspaper publishers to use news with 25% recycled content by 1991 and 50% by 2000. Commission to study market opportunities. Plastic coding
				Florida	
1988	30%	1994	Product ban on detachable pull-rings, some nonbiodegradable plastic packaging. Disposal ban on tires, and lead-acid batteries	Advance disposal fees, sales tax, business registration. Oil overcharge monies. Solid waste management trust fund	Additional advance disposal fees if recycling waste targets not met. Plastics coding. State agencies to use compost and recovered construction materials
				Indiana	
1990	35% 50%	1996 2001	Disposal ban on designated recyclables will be implemented if deemed necessary	Statewide disposal surcharge	Countries required to form solid waste management districts. Low-interest loans for recycling organizations.

Table 10.5 Solid waste legislation by some states of U.S.A. (Grogan 1993) (continued)

Date passed	WR/R[a] goal	Completion date	Product and disposal bans	Funding	Other unique characteristics
				Maine	
1989	25% 50%	1992 1994	Product ban on multilayer juice containers, plalstic cans, 6-pack yokes	Disposal surcharge. Advance disposal fee on special wastes	30% tax credit on recycling equipment purchases. Creates Waste Management Agency. State agencies to purchase recycled paper. Commercial sector to recycle
				Washington	
1989	50%	1995	Disposal ban on lead-acid batteries	Advance disposal fee on tires. Solid waste collection tax. County disposal surcharge	County solid waste management plans to include WR/R education programs and market strategies. Market development committee established
				Pennsylvania	
1988	25%	1997	None	Disposal surcharge	Municipality recycling programs required. Businesses, gogernment offices, hospital and schools required to source separate. Funding for market research and development. Low interest loans available to recycling companies.

[a] WR/R = waste reuse and recycling

10.5 MONITORING AND CONTROL OF FACILITY PERFORMANCE

One of the essential aspects of waste recycling program is monitoring of facility performance. This is required for the analysis and evaluation of the chosen technology in achieving its objective. One of the many reasons why some of the objectives of a planned program are not attained are due to failures of the concerned persons or agencies to monitor the project implementation and evaluate operational problems which are generally dealt only at the critical stage. To avoid such failures and prevent the problems from becoming a crisis it is obligatory for all projects to formulate a monitoring program. A monitoring set-up for facility performance depends on:

1. Objectives defined for monitoring;
2. Data evaluation, analysis and documentation;
3. Equipment monitoring efficiency; and
4. Organizational infrastructure

10.5.1 Objectives defined for monitoring

In view of the present socio-economic situations of most societies, the pragmatic objectives of such monitoring system can be stated as:

1. Efficient control and regulation of the present system;
2. Emission analysis and evaluation;
3. Catering for the future needs; and
4. Analysis of public response for system interaction.

Effective control and regulation of the system

Monitoring is a present day scientific tool for efficient management of a system. As in most systems, efficiency is evaluated on an economical scale, and making sure that the system is working on the positive side. Based on the technology selected, the monitoring process is regulated depending on the inflow of the suitable wastes and demand of the recycled product. Examples for this are the slow-rate (irrigation) system where certain crops are grown from wastewater application (see Chapter 8) and fish production in waste-fed ponds (see Chapter 6), etc.

Emission analysis and evaluation

The purpose of monitoring in this context is to check the addition of pollutants to the environment from waste recycling programs. Practically it can be better explained by the analysis and evaluation of the recycled products such as pathogen contents in the wastewater-irrigated crops or fish raised in waste-fed ponds and nutrient balances in the composted products or digester slurry.

Catering for future needs

The present-day technologies are changing rapidly with time. Any system has to be flexible to cope up with future changes, and this applies to the case of waste recycling and recovery. One of the solutions therefore is to foresee the changing trend and restructure the waste recycling system to take care of future demands. The increased reuse of organic wastes may be cited as an example. In the past, animal manure was applied direct on a agricultural land, but currently it is being fed to anaerobic digesters to produce biogas and the digested slurry applied to crop lands in an engineered manner.

Analysis of public response for system interaction

A system can exist and grow only when it is patronized by the people for whom it has been established. In the context of developing countries, the waste recycling system adopted should coincide with the social attitudes and must be compatible to the people. A typical example is the gradually diminishing public defiance in Asian countries for consuming crops fertilized with composted materials or wastewaters.

An efficient monitoring system must then have its feed back from end users and should consider it with due concern.

10.5.2 Data evaluation, analysis, and documentation

Monitoring relies on statistical information generated from continuous study of the various parameters of the waste recycling system and their thorough analysis. Some common parameters used in waste recycling systems are BOD_5, nutrients and pathogen contents, etc. These parameters give information on the quality and characteristics of the incoming waste and the output or recycled products. The above data help to identify trends in performance and phenomena of the process and, in many cases, to establish empirical formulae.

Documentation of data is equally important to keep relevant and reliable data for future reference and decision-making. In all cases easy to handle and systematic storage is a must since the long-term evaluation of the process is mostly based on these data.

10.5.3 Equipment monitoring

A major part of waste recycling technology is the various items of equipment used in the program. These can vary widely in nature according to use. Monitoring of these assets is equally important since they can influence the system efficiency to a great extent. For example, a leak in the gas holder tank of a digester can reduce its efficiency significantly.

10.5.4 Organizational infrastructure

The organization for monitoring depends largely on the extent and intensity of the program. In most cases the program is not for a central based system, but for large-scale people participation. For a centrally based recovery and recycling program, reasonably well-qualified technicians (but less in number) are required. Where the program is more public intensive and emphasis is placed on making it a social habit, a large number of people who may not necessarily be with higher qualification but with more dedication and commitment are required. In such cases large-scale training and apprenticeship are more beneficial.

The financial aspects of these establishments depend on their size and manpower involvement. In all cases the central organization should be adequately furnished with basic requirements such as laboratory and training units so that feedbacks from the field and the present knowledge can be better blended to support the implementation of the waste recycling programs.

10.6 CASE STUDIES OF WASTE RECYCLING MANAGEMENT PROGRAM

10.6.1 Biomass management by the Montreal Metropolitan Community, Canada (Frigon and Guiot 2005)

The Quebec Waste Management Policy (1998-2008) is requesting the municipalities within its province to prepare a waste management plan including a global objective of 60% reduction of the solid wastes destined for sanitary landfills. The Montreal municipality which has a population of 3.5 millions produces about 5.8 million tons of solid wastes annually. Based on a study of various management scenarios, it was found that anaerobic digestion of the solid wastes was the most cost-effective solution resulting in a potential CH_4 gas generation of 17-140 Mm^3 which can be used to produce electricity of 53,000-440,000 MWh equivalent to a revenue of 17 million Canadian $ annually. This solution would lead to a reduction of greenhouse gas emission of 62,000-500,000 tons of CO_2-equivalents annually.

This environmental policy initiated by the Quebec Province is considered an effective tool for the municipalities to determine sustainable solutions to manage their solid wastes with the beneficial results in pollution control, energy recovery and reduction of greenhouse gas emission to the atmosphere.

10.6.2 Sanguan Wongse Industries Co., Ltd., Nakhorn Ratchasima province, Thailand. (www.swi.co.th)

The Sanguan Wongse Industries Co., Ltd., located about 200 km northeast of Bangkok city, Thailand, uses about 4,000 tons/day of fresh cassava roots to produce 1,000 tons/day of starch and related products for local consumption and exports to several countries worldwide. The tapioca production processes (see section 2.3.1) generate 9,600 m^3/day of wastewater having a COD concentration of 30,000 mg/L.

Figure 10.2 Anaerobic baffled reactors (ABR) covered with plastic sheets for wastewater treatment and biogas production

As part of its efforts to meet the ISO 9002 standard for quality assurance and the Thailand brand logo for high quality export certification of the Department of Export Promotion of Thailand, the company has employed anaerobic baffled reactors (ABR) to treat 60% of this wastewater volume (Figure 10.2). This reactor is able to remove more than 90% of the COD input with CH_4 gas production of 70,000 m^3/day, equivalent to the CH_4 production rate of 0.35 m^3/kg COD (similar to the theoretical value as given in section 4.5). The CH_4 gas is fed to a co-generator to produce boiler steam and electricity for uses in the starch production processes, resulting in a cost saving of approximately 35,000 Baht (US$ 900) per day. The remaining 40% of the wastewater together with the ABR effluent are treated in a series of waste stabilization ponds. The pond effluent, which meets the Thailand effluent standard (Table 10.6), is discharged to a nearby river.

Table 10.6 Thai industrial effluent standard (www.pcd.go.th)

Parameters	Standard value	Method for examination
1. pH value	5.5-9.0	pH meter
2. Total dissolved solids (TDS)	not more than 3,000 mg/L depending on receiving water or type of industry under consideration of PCC[a] but not exceed 5,000 mg/L	Dry evaporation 103-105 °C, 1 hour
3. Suspended solids (SS)	not more than 50 mg/L depending on receiving water or type of industry or wastewater treatment system under consideration of PCC but not exceed 150 mg/L	Glass fiber filter disc
4. Temperature	not more than 40°C	Thermometer during the sampling
5. Color and odor	not objectionable	Not specified
6. Sulphide as H_2S	not more than 1.0 mg/L	Titration
7. Cyanide as HCN	not more than 0.2 mg/L	Distillation and Pyridine barbituric acid method
8. Fat, oil & grease (FOG)	not more than 5.0 mg/l depending of receiving water or type of industry under consideration of PCC but not exceed 15.0 mg/L	Solvent extraction by weight
9. Formaldehyde	not more than 1.0 mg/L	Spectrophotometry
10.Phenols	not more than 1.0 mg/L	Distillation and 4-aminoantipyrine method
11.Free chlorine	not more than 1.0 mg/L	lodometric
12.Pesticides	not detectable	Gas chromatography
13.Biochemical oxygen demand (BOD_5)	not more than 20 mg/L depending on receiving water or type of industry under consideration of PCC but not exceed 60 mg/L	Azide modification at 20 °C , 5 days
14.Total Kjedahl nitrogen (TKN)	not more than 100 mg/L depending on receiving water or type of industry under consideration of PCC but not exceed 200 mg/L	Kjeldahl
15.Chemical oxygen demand (COD)	not more than 120 mg/L depending on receiving water of type of industry under consideration of PCC but not exceed 400 mg/L	Potassium dichromate digestion

Table 10.6 Thai industrial effluent standard (www.pcd.go.th) (continued)

Parameters	Standard value	Method for examination
16.Heavy metals		
16.1. Zinc (Zn)	not more than 5.0 mg/L	Atomic absorption spectro-photometry; Inductively coupled plasma (ICP)
16.2. Chromium (Hexavalent)	not more than 0.25 mg/L	
16.3. Chromium (Trivalent)	not more than 0.75 mg/L	
16.4. Copper (Cu)	not more than 2.0 mg/L	
16.5. Cadmium (Cd)	not more than 0.03 mg/L	
16.6. Barium (Ba)	not more than 1.0 mg/L	
16.7. Lead (Pb)	not more than 0.2 mg/L	
16.8. Nickel (Ni)	not more than 1.0 mg/L	
16.9. Manganese (Mn)	not more than 5.0 mg/L	
16.10. Arsenic (As)	not more than 0.25 mg/L	Atomic absorption spectrophotometry; Hydride generation, or plasma emission spectroscopy; Inductively coupled plasma : ICP
16.11. Selenium (Se)	not more than 0.02 mg/L	
16.12. Mercury (Hg)	not more than 0.005 mg/L	Atomic absorption cold vapour technique

[a] PCC = Pollution Control Committee, Thailand

This case study demonstrates the significance of ISO and the government certification standards in encouraging the industry to collect, treat and recycle its wastewater. The overall benefits are cost saving to the industry and protection of the water and air environment.

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10.8 EXERCISES

10.1 Find out the existing regulations and measures dealing with waste recycling in your country and compare them with those in Tables 10.3-10.5.

10.2 You are to develop a program of wastewater land treatment in your country. Draw a strategic plan for implementation (e.g. similar to that shown in Figure 10.1) so that this waste-recycling program will be sustainable.

10.3 Find out the basis for development of regulatory standards for effluent discharges in your country. How can these standards be applied for waste recycling activities?

10.4 In your opinion, should organic waste recycling programs be carried out in rural or urban areas of your country?

10.5 What are the present institutional set-ups for waste recycling programs in your country? Give recommendations for improvement of these set-ups.

Index

This book covers the principles and practices of technologies for the control of pollution originating from organic wastes (e.g. human faeces and urine, wastewater, solid wastes, animal manure and agro-industrial wastes) and the recycling of these organic wastes into valuable products such as fertilizer, biofuels, algal and fish protein and irrigated crops.

Each recycling technology is described with respect to:

- Objectives
- Benefits and limitations
- Environmental requirements
- Design criteria of the process
- Use of the recycled products
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This new edition, an update of the previous book, is a response to the emerging environmental problems caused by rapid population growth and industrialization. It describes the current technology and management options for organic waste recycling which are environmentally friendly, effective in pollution control and yield valuable by-products. Every chapter has been revised to include successful case studies, new references, design examples and exercises. New sections added to the 3rd edition include: Millennium development goals, waste minimization and cleaner production, methanol and ethanol production, chitin and chitosan production, constructed wetlands, management and institutional development.

This is a textbook for environmental science, engineering and management students who are interested in the current environmental problems and seeking solutions to the emerging issues. It should be a valuable reference book for policy makers, planners and consultants working in the environmental fields.

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