Resource Recovery from Faecal Sludge using Constructed Wetlands

A survey of the literature

UWEP Working Document

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PREFACE

In the sanitation sector there is growing attention for issues of sustainability. This interest is expressed in, for example, an increasing number of initiatives that are focused on the closing of water and nutrient cycles and the recovery and reuse of these resources. There is not much experience with resource recovery from non-sewered on-site sanitation facilities in developing countries. In this respect is has been very challenging to give a state-of-the-knowledge of resource recovery from faecal sludge using wetlands.

It was not always easy to retrieve the literature, so I am grateful to the persons who contributed to this report by sending information, reviewing the draft document and giving general support. I would like to mention several people, because without their contribution this report would not have been as it is. First, I want to mention Martin Strauss and Udo Heinss (SANDEC, Switzerland), who have a broad experience in faecal sludge treatment. They took time to read the draft and made valuable comments on the contents and structure of the document. They were an essential source of information. Also, I would like to thank Annelies Balkema (Eindhoven University of Technology, the Netherlands), Gregory Rose (IDRC, Canada) and Dhrubajyoti Ghosh (CMW SA, India) for sending information, reference lists and comments. Finally, I would like to thank all the people of WASTE for their support and co-operation.

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ABBREVIATIONS

BOD	Biochemical Oxygen Demand
C	Carbon
COD	Chemical Oxygen Demand
CW	Constructed Wetland
FS	Faecal sludge
ISWM	Integrated Solid Waste Management
K	Potassium
N	Nitrogen
NH_4-N	Ammonium-nitrogen; The amount of nitrogen present as ammonium
NO_3-N	Nitrate-nitrogen; The amount of nitrogen present as nitrate
p.e.	Person equivalent or inhabitant equivalent (i.e.). Number of daily loading equivalents per capita.
P	Phosphorus
SS	Suspended Solids
TKN	Total Kjeldahl Nitrogen
TS	Total Solids
TSS	Total Suspended Solids
UWEP	Urban Waste Expertise Programme
WHO	World Health Organisation
WSP	Waste Stabilisation Pond

GLOSSARY

Faecal Sludge:	Sludges of variable consistency collected from so-called on-site sanitation systems, such as latrines, non-sewered public toilets, septic tanks and aqua privies. The faecal sludge comprises varying concentrations of settleable or settled solids as well as of other, non-faecal matter (Heinss *et al.*, 1998)
Nightsoil:	Human excreta, with or without anal cleaning material, which are deposited in a bucket or other receptacle for manual removal (often taking place at night) (Franceys *et al.*, 1992)
Septage:	The combination of sludge, scum and liquid pumped from a septic tank (Metcalf & Eddy, 1991).
Sewage sludge:	Sludge produced in wastewater treatment plants.

SUMMARY

A large part of the urban population in low-income countries is not served with proper sanitation. Although the public health aspects are of great importance, the options for the recovery of the resources in faecal sludge should not be overlooked. From the perspective that waste is a mixture of valuable resources, faecal sludge should not only be treated and disposed of in a safe and environmental manner, but its components (i.e. water, nutrients, organic matter) should be applied for other purposes e.g., for fertilisation or the production of biomass.

Although not much is reported about faecal sludge treatment and reuse, there are some possibilities for treatment and reuse on a small scale. The treatment of faecal sludge on a neighbourhood scale has certain benefits and drawbacks compared with centralised treatment. Neighbourhood scale treatment can result in lower transportation cost of the sludge. After treatment the sludge has a higher solids content which makes it cheaper to transport the sludge to more remote areas.

Faecal sludges are sludges of variable consistency collected from so-called on-site sanitation systems, such as latrines, non-sewered public toilets, septic tanks and aqua-privies. To some extent, it can be compared with sewage sludge, which is a co-product of conventional wastewater treatment processes. This means that processes for the treatment and disposal of sewage sludge might be applicable for faecal sludge treatment.

For the treatment of sewage sludge, different technologies have been developed and are applied in most of the industrialised countries. Not all of these treatment processes aim at resource recovery. Sludge treatment processes as mechanical sludge dewatering and incineration require high-tech installations and consume a lot of energy. For example, sludge dewatering by sedimentation and composting of the sludge can be done with much lower energy input.

Constructed wetlands for the treatment of faecal sludge might be a powerful tool to raise the quality of life of local communities in developing countries. The waste can be treated as a valuable resource, since the yields of wetlands are valuable products. Resource recovery from faecal sludge can take place in different ways:

- A direct reuse of the faecal sludge in agriculture or aquaculture (e.g. fertilisation, soil conditioning).
- The reuse of the effluent of treatment systems, such as ponds and wetlands (e.g. irrigation, fertilisation).
- The reuse and further treatment of the biomass produced in wetlands or ponds (e.g. composting, energy production, production of building materials, animal feed and fibres).

The integration of faecal sludge treatment and the production with wetlands leads to promising systems in which waste is a valuable resource. In Asia, Latin America and Africa various integrated systems have been operated for years.

CHAPTER 1 INTRODUCTION

1.1 Public health

Regarding public health, aspects sanitation is a very important issue in the process of development. Proper sanitation is one of the factors which are critical for human and economic development (IRC, 1995). Today, inadequate sanitation is one of the principal environmental health problems facing poor urban residents in developing countries. Despite massive investments in sanitation during the water and sanitation decade, approximately 40 percent of the urban population in low-income countries were still not serviced in 1995 (Watson, 1995).

Previous research on on-site sanitation technologies for faecal sludge treatment has been focusing primarily on the pathogen removal and die-off, treatment performance with respect to pollution control parameters and the public health effects of the reuse (Cross & Strauss, 1985; Heinss *et al.*, 1997; Heinss *et al.*, 1998; Strauss, 1998).

1.2 Resource recovery with wetlands

Although the public health aspects are of great importance, the options for the recovery of the resources in faecal sludge should not be overlooked.

Organic waste (kitchen waste, plant material, human excreta) is not only a (possible) source of pathogens which must be disposed of as quickly as possible, it contains a lot of valuable components that can be reused for several purposes. It contains organic matter, water and nutrients. There are possibilities to reuse these components, for example, in agriculture, aquaculture and for energy production.

The use of organic waste as a fertiliser and soil conditioner in aquaculture and agriculture has been practised for many years in different areas around the world (Evans, 1998; Edwards, 1992). Sewage sludge is also a valuable organic manure and provides recycled nitrogen and phosphorus (Towers & Horne, 1997).

For similar reasons, faecal sludge can be used as a source of fertiliser. Faecal sludge consists of human faeces and urine and has a high concentration of organic matter and nutrients. The pathogen concentration of the faecal sludge, however, poses serious risks to the health of the people who are in contact with the sludge, which applies to the larger part of the population of many urban areas due to improper sanitation facilities and unsafe disposal practices.

Constructed wetlands for the treatment of faecal sludge might be a powerful tool to raise the quality of life of local communities in developing countries. The advantages of the systems are the simple technology, low capital costs and the low maintenance required.

Besides that, waste can be treated as a valuable resource, since the yields of wetlands are valuable products. Potential examples of the use of the products of wetlands are (Denny, 1997):

- The nutrient rich effluent can be used as a trickle-feed to ridge and furrow cultivation.
- The effluent can enrich fish ponds, which will increase the phyto-plankton growth on which fish feed.
- The (dried) sludge together with the standing wetland crops can be used as a nitrogen source in co-composting or as a soil conditioner and fertiliser.

In spite of the advantages of the use of constructed wetlands for the treatment of sewage or faecal sludge, the use of these systems is not widespread in developing countries. Balkema *et al.* (1998), Denny (1997) and Van Lier *et al.* (1998) report reasons for the relatively slow spread of the use of constructed wetlands (and other so called 'low-cost' technologies) in developing countries:

- Aid programmes from industrialised countries tend to favour the more overt technologies which have commercial spin-off for the donors.
- Experts from the developed world are often entrenched in appropriate technologies for *their* own countries and are unable to transfer their conceptual thinking to the realities and cultures of the third world.
- Experts from developing countries have largely been educated in the 'conventional' technologies and have only limited access to information and knowledge on new technologies.
- There has been a tendency to translate 'northern' technologies to tropical environments, instead of assisting developing countries to develop their own technologies.

1.3 Objectives and scope this report

The Urban Waste Expertise Programme (UWEP) aims at generating knowledge and expertise on integrated sustainable waste management (ISWM) and making it more easily accessible to the various stakeholders in urban waste management. A part of UWEP deals with non-sewered on-site sanitation, i.e. collection, transfer, treatment, reuse and disposal of faecal sludge. In this context the aim of this report is to contribute to an increased knowledge of, and a better understanding of the possibilities for reuse and resource recovery of (components of) faecal sludge among people involved in ISWM.

The objective of this report to describe a state-of-knowledge on the possibilities for the treatment of faecal sludge with wetlands and the recovery and reuse of the valuable sludge components for aquacultural, agricultural and other purposes. Important issues are the types of treatment that can be applied and the integration of treatment and the generation of marketable products.

Before going into detail on treatment technologies, aspects of scale are discussed in Chapter 2. The characteristics of faecal sludge are mentioned in Chapter 3. A range of sludge treatment technologies that may be more or less appropriate for the application in developing countries are mentioned in Chapter 4. Wetlands may offer possibilities for recovering resources from faecal sludge. Different types of wetlands are described in Chapter 5. Chapter 6 focuses on the possibilities of using the yields of wetlands and in the final chapter (7) some recommendations for further research are given.

CHAPTER 2 NEIGHBOURHOOD SCALE

2.1 Advantages

Various authors have argued that sustainable sanitation and resource recovery should take place at a decentralised level or neighbourhood scale (Rijnsburger, 1998; Van Lier, 1998; Watson, 1995). Reasons that are mentioned are the ecological sustainability and integrity, economic sustainability and best practices.

A definition of decentralised wastewater management is given by Crites & Tchobanoglous (1998): *Decentralised wastewater management involves the collection, treatment, disposal and/or reuse of wastewater from individual homes, clusters of homes, and isolated community and commercial facilities at or near the point of generation.*

In the industrialised countries the major part of the population relies already on centralised waterborne sewerage, which makes it difficult to realise treatment and reuse at an on-site or neighbourhood scale. The sanitation situation that exists in the majority of the developing countries is that the larger part of the population is provided with on-site sanitation. This may be a good starting point for decentralised sanitation.

The involvement of users and economic considerations plead for treatment and reuse systems at neighbourhood scale. First, neighbourhood scale treatment and reuse enable the population to be involved with the systems. People are aware of the direct link between their wastewater disposal and the treatment system. They can see it (and smell it?) or probably use the treated water for e.g. household purposes or urban agriculture. Due to the small-scale technology complain and correct systems in case of system failure may be more adequate than in case of centralised systems. So, people who are involved with the treatment and reuse will have willingness to pay for the services (Rijnsburger, 1998).

Second, there is always the economic question whether the treatment and reuse should take place on-site or off-site. An important consideration is the cost of transportation. When rather long transportation distances are needed for off-site treatment or reuse, it becomes important to concentrate the material (in this case Faecal Sludge). An example from Bangkok, Thailand, makes clear that the direct use of nightsoil for agricultural purposes was not an economic option for that situation. The agricultural land is far away from the area where the nightsoil is produced. So it would be expensive to transport the nightsoil, with a relatively high water content, to the agricultural sites. One of the most feasible solutions in the Bangkok case is to de-water the nightsoil on-site followed by the transportation of the concentrated nightsoil to the agricultural sites (Stoll & Parameswaram, 1996).

Reed *et al.* (1994?) also argues that transportation of sewage sludge from the treatment plant to the point of disposal or reuse is a major factor in the costs of sludge management. This means that, besides other reasons, the transportation costs may be a decisive factor for the choice between on-site or off-site treatment and even reuse.

2.2 Disadvantages

Neighbourhood scale treatment may not be a suitable option for each situation as there are some unattractive sides as well. One of the main objections against neighbourhood scale treatment and reuse of black water and/or sludge is the high content of pathogens present in the waste. Especially in densely populated neighbourhoods the risk of a rapid spreading of diseases is relatively high.

For the treatment of faecal sludge in wetlands it can be questioned whether they are suitable for application on neighbourhood scale, because wetlands usually require a relatively large area. Also wetlands are open systems, which may cause health risks through direct contact of people with the wastewater or sludge and small parts of open water as niche for insect breeding. Furthermore, wetlands within a community may cause nuisance: they are a good habitat for unwanted animals such as muskrats and in case of malfunctioning the wetlands may produce bad odours.

However, it is assumed that the success of the application of a wetland depends heavily on the way of operation, which means an optimal performance together with a minimum of health risks.

Although on-site or neighbourhood treatment and reuse may offer advantages with regard to the transportation costs, it is possible that the investment costs per capita are higher than when a centralised system would have been installed.

Many people have developed ideas about decentralised or neighbourhood scale treatment of wastewater and/or faecal sludge. Still, there are a lot of uncertainties and questions to be solved. Also the best solution (technical, economic, social and ecological) will not be the same for every situation, as the local conditions differ from place to place.

CHAPTER 3 FAECAL SLUDGE

3.1 Human excreta

The amount of faeces and urine produced per capita per day may vary for different regions. Reasons for this can be different dietary habits and climate conditions. The amount of faeces produced ranges from 69 - 520 g/cap·day, while the urine production ranges from 845 - 1200 g/cap·day (Table 3.1).

Table 3.1 The amount of faeces and urine produced per capita per day in nightsoil for different regions

	faeces (g/cap·d)	urine (g/cap·d)
Africa (Mann, 1976)	400	1200
USA (Snell, 1943)	86	1055
China (Snell, 1943)	69	845
Europe, North America (Edwards, 1992)	100 - 200 (wet faecal weight)	
developing countries (Edwards, 1992)	130 - 520 (wet faecal weight)	
Vietnam (Nimpuno, 1983)	1370 (faeces + urine)	
Thailand (Stoll & Parameswaran, 1996)	1000 (faeces + urine)	

A characterisation of human excreta produced per capita is given by SANDEC (1997) (Table 3.2). The total amount of fresh human excreta produced per capita per day is about 1.5 litres. The amount of septage and sludge from unsewered toilets and pits is different, due to differences in the use of water for cleansing, evaporation and infiltration of liquids into the soil and degradation during storage.

Table 3.2 Faecal sludge per capita contributions

Variable	Fresh excreta	Septage [1]	Sludge from unsewered public toilets [2]	Pit latrine sludge [2]
BOD (g/cap·day)	45	1	16	8
TS (g/cap·day)	110	14	100	90
TKN (g/cap·day)	10	0.8	8	5
l/cap·day	1.5 (faeces and urine)	1	2 (includes water for toilet cleansing)	0.15 - 0.20

[1] Based on a FS collection survey conducted in Accra, Ghana.
[2] Only assuming top portion of pit, being emptied.

3.2 Faecal sludge

Faecal sludge is defined by Heinss *et al.* (1998) as:

Sludges of variable consistency collected from so-called on-site sanitation systems, such as latrines, non-sewered public toilets, septic tanks and aqua privies. The faecal sludge comprises varying concentrations of settable or settled faecal solids as well as of other, non-faecal matter.

A general indication of faecal sludge characteristics is given by SANDEC (1997) (Table 3.3). Concentrations of COD, ammonium, SS and helminth eggs in FS are much higher than in sewage due to the lower water contents.

Table 3.3 General faecal sludge characteristics

Item	High strength	Low strength	Sewage for comparison
Example	Public toilet or bucket latrine sludge	Septage	Tropical sewage
Characterisation	Highly concentrated, mostly fresh FS; stored for days or weeks only	FS of low concentration; usually stored for several years; more stabilised that high strength sludge	
COD (mg/l)	20,000 - 50,000	< 10,000	500 - 2,500
COD/BOD	5:1 ... 10:1		2:1
NH_4-N (mg/l)	2,000 - 5,000 [1]	< 1,000	30 - 70
TS	≥ 3.5%	< 3%	< 1%
SS (mg/l)	≥ 30,000	≈ 7,000	200 - 700
Helminth eggs (no./l)	20,000 - 60,000	≈ 4,000	300 - 2,000

[1]Sludge from bucket latrines will probably contain much lower amounts of ammonium-nitrogen as in most cases urine is not collected in bucket latrines (Strauss, pers. comm., 1999).

3.3 Nightsoil

Regarding the definition, nightsoil may be comparable to faecal sludge:

Nightsoil is human excreta, with or without anal cleansing material, which are deposited in a bucket or other receptacle for manual removal (Franceys *et al.*, 1992).

However, according to the abovementioned definition it can be expected that nightsoil has a considerable higher solids content than faecal sludge, because faecal sludge typically originates from sanitation systems that need a form or water supply. Also nightsoil, as being the contents of bucket latrines, will contain less NH4-N, as urine is in most cases not collected. However, in many cases the term nightsoil is used for other types of sludges as well.

Edwards (1992) calculated that the strength of adult nightsoil in developing countries might be 21,700 mg BOD_5/l, based on a daily total volume of excreta and anal cleansing material of 1.5 l/adult. This means that nightsoil in the narrow sense of the word as characterised by Edwards and the faecal sludge are comparable. Stoll & Parameswaran (1996) reported for Thailand that the Kjeldahl nitrogen and total Phosphorus concentration in nightsoil (based on wet weight) are 27.5 g/kg and 10 g/kg respectively.

For comparison purposes Table 3.4 also mentions some data on nutrient contents of plant matter and different types of manure.

With respect to the nutrients, the composition of human excreta is comparable with pig manure, except from the nitrogen content which is higher by a factor 2 for excreta. Cow manure has in general lower nutrient concentrations than human excreta (Heinss *et al.*, 1998).

Table 3.4 Nutrient contents in excreta, plant matter and manure (Heinss *et al.*, 1998; Cross & Strauss, 1985)

	% of dry solids		
	N	P_2O_5	K_2O
Human excreta*	9-12	3.8	2.7
Fresh nightsoil*	10.4-13.1	2.7-5.1	2.1-3.5
Plant matter	1-11	0.5-2.8	1.1-11
Pig manure	4-6	3-4	2.5-3
Cow manure	2.5	1.8	1.4

* Comprises faeces, urine and ablution water

3.4 Sewage sludge

Common value for sewage sludge is a solids content of around 2%. Anaerobically digested sludge generally has a higher solids content, while aerobic sludge has a lower solids content (De Maeseneer, 1997). Untreated primary sludge from activated sludge plants has a typical TS content of 5 % (range 2 - 8 %) (Metcalf & Eddy, 1991). In general, the nutrient concentrations of sewage sludge are lower than in human excreta and faecal sludge (Table 3.5).

Table 3.5 Nutrients in sewage sludge for different countries (Wang, 1997)

	% of dry solids		
	N	P	K
China	2.35	1.05	0.74
UK	-	1.5-1.7	0.2
USA	-	2.3	0.5
South Africa	2.8	1.6	0.3

3.5 Comparison

Although there are some differences, sewage sludge is to some extent comparable with faecal sludge and nightsoil. This means that the technologies that are in use for treatment, resource recovery and reuse of e.g. sewage sludge may be appropriate for faecal sludge treatment.

A difference is that faecal sludge usually contains less heavy metals and persistent organic pollutants than sewage sludge (Heinss *et al.*, 1998; Wang, 1997). The reason for this might be that sewerage systems in general receive not only domestic wastewater, but also wastewater from (small) industries, containing more heavy metals.

A remark must be made about the main difference between various types of sludge i.e. the degree of stabilisation which influences the organic matter content and especially the nitrogen content e.g., long stored septage contains 10 % of the nitrogen of fresh undigested faecal sludge like public toilet sludge. Also, aerobically stabilised sludge contains much less organic matter than sewage sludge from a high rate activated sludge process. These differences result in different characteristics of the various sludges. For example, aerobically stabilised sludge from extended aeration plants has a good settling behaviour, while the fertiliser potential is rather low (due to a relatively high NO_3-N content). Fresh undigested sludge should first be digested prior to reuse, but it has a high fertiliser potential (relatively high NH_4 and organic nitrogen content). These differences will result in different possibilities for treatment processes and potentials for resource recovery (Heinss, pers. comm., 1999).

CHAPTER 4 SLUDGE TREATMENT

Although the application of untreated sludge is attractive because of its simplicity and least loss of nitrogen as a plant nutrient, in most cases sludge has to be treated prior to reuse and even before it is dumped or disposed of. Reasons are the high content of water, making it costly to transport the sludge, and the presence of pathogens and possibly heavy metals. This chapter lists various technologies for pre-treatment and final treatment of sludge. Not all technologies are applicable for non-sewered situations in developing countries, due to requirements of highly skilled expertise, capital costs and energy.

4.1 Solids/liquid separation

Dewatering or the separation of the solids and liquids of the sludge is primarily meant to reduce the volume of the sludge and to increase the dry matter content. Most of the processes described in this paragraph are normally used for the treatment of (primary and secondary) sewage sludge, except the composting and vermi-composting processes which are also used for treatment or handling of other organic wastes.

As said in Chapter 3, sewage sludge and faecal sludge can be compared with each other, which means that most figures given for sewage are also representative for faecal sludge treatment. Different processes or technologies may be suitable to a different extent for the application with FS, considering the characteristics of the sludge and also the non-technological conditions (economic, social, etc.)

4.1.1 Gravity solids/liquid separation

Gravity dewatering makes use of sedimentation. Also, evaporation processes increased by wind and solar energy contribute to the reduction of the water content of the sludge.

Sedimentation tanks

Using lagoons or sedimentation basins for sewage sludge dewatering a TS contents of 10 - 35% and a volume reduction of 40 - 50% (and even more when one starts with a solids content of 2 - 5 %) can be achieved (NVA, 1994; Strauss, 1999). In sedimentation tanks sedimentation and flotation of solid material separate the water and sludge. Heinss *et al.* (1997) reported about a FS sedimentation/thickening basin, in Accra, Ghana, in which a thickening concentration TS ≤ 15% could be attained.

Using operating cycles of four loading weeks and four resting weeks, the following removal percentages can be expected with this type of settling tanks:

BOD and COD removal:	50%
Suspended solids removal:	60 - 80%
Helminth eggs removal:	50%

A TS loading of 1,200 kg TS/ $m^2 \cdot yr$ was applied, which meant a relatively small required area (m^2) per capita of 0.006 (based on FS quantity = 1 l/cap.day; TS of the untreated FS = 20 g/l).

Drying beds without plants

Gravity dewatering can also take place in (unplanted) drying beds. Similar to lagoons, drying beds also require much space. Dewatering is attained both by evaporation and seepage.

According to Heinss *et al.* (1997) 40 - 70% TS content in the dewatered faecal sludge may be attained within 8-12 days, with loading rates of 100 - 200 kg TS/$m^2 \cdot yr$. These loading rates are considerably lower than, for example, the loading rates that can be applied in sedimentation tanks, which results in a larger area per capita (0,05 m^2/cap). However, the effluent of drying beds needs less polishing than the effluent of sedimentation tanks, because the following removal percentages were achieved:

COD removal:	70 - 90%
SS removal:	≥ 95%
Helminth egg removal:	100% (heavily dependent on the residence time)

Also a considerable part (40 - 60 %) of the inorganic nitrogen (NH_4-N; NH_3-N) is removed due to the combined effect of nitrification and ammonia stripping.

Based on a questionnaire and visits to wastewater treatment plants in the USA, Kim and Smith (1997) reported that the type of sludge influences the loading rates that can be applied on sand-drying beds without plants. Using different drying bed criteria, the solid loading rates for open sand-drying bed range from 64 to 113 kg/$m^2 \cdot yr$. For anaerobic sludge, the EPA recommended 100 to 160 kg/$m^2 \cdot yr$. as sand drying bed design criteria. These conventional unplanted sand-drying beds are simple to operate and maintain, and are inexpensive to build. Some disadvantages are, however, that dewatering can take 2 to 4 weeks (depending on the climate, soil type etc), the removal of the dried sludge requires intensive labour and there is always the danger of clogging or low dewaterability potential with undigested or only partly dewaterd sludges.

4.1.2 Mechanical solids/liquid separation

Mechanical dewatering methods have low area requirement and the TS content of the solid fraction can be controlled precisely. Mechanical methods are characterised by high capital costs, high-energy consumption (1 - 10 kWh/m^3) (STORA, 1981) and the need for adding chemicals for conditioning.

Most common processes applied are:

- Vacuum filtering
- Filter pressing
- (Chemical added) centrifuging
- Belt filter pressing

The TS content that can be achieved by mechanical dewatering processes is comparable with natural dewatering processes: 15 - 45% (NVA, 1994).

4.2 Digestion

The digestion of faecal sludge is not primarily meant for solid / liquid separation. During the digestion process the organic material is decomposed. The biogas produced during the process can be collected and used for cooking or heating, while the effluent of the digesters can be used for plant fertilisation and soil amendment purposes. The sludge that remains in the digester has to be removed and usually needs some further treatment e.g. drying, composting, land application or incineration.

Zhao Xihui reports about four different types of digesters that are used in China for nightsoil treatment (Xihui, 1988). These digesters can achieve a high parasitic ova reduction: > 93%. The effluent of the digesters needs a post treatment before discharging into surface water or sewer systems. The application of biogas digesters resulted in a reduced prevalence of infectious diseases and also the density of flies decreased remarkably.

In Guatemala dome-shaped Chinese type digesters have been tested. Latrines fed the digesters. The experiments made clear that the low temperatures and the low air pressure had a negative effect on the treatment process. The underground-type Chinese digester, used as a latrine, produced biogas, solids and a relatively clear effluent. The solids and effluent can be used as fertiliser as the effluent contains high concentrations of nitrogen, phosphorus and potassium. The pathogen concentration in the effluent was acceptable for reuse in agriculture and fishponds (Estrada *et al.*, 1986).

4.3 Incineration and combustion

Incineration, which is a complete combustion, is defined as the rapid exothermic oxidation of combustible elements in fuel. Different types of combustion processes are in use, suitable for the application of sludge as (part of the) fuel. Major advantages of thermal sludge reduction are a maximum volume reduction, the destruction of pathogens and toxic compounds and energy recovery. Disadvantages are high capital and operation cost, highly skilled operating and maintenance staffs are required, the residuals produced (air emissions and ash) may have adverse environmental effects and the disposal of residuals, which may be classified as hazardous wastes, may be uncertain and expensive (Metcalf & Eddy, 1991).

4.4 Composting

4.4.1 Composting processes

Composting is a process of biological breakdown of solid organic matter to produce a humic substance (compost) which is valuable as a fertiliser and soil conditioner. Nightsoil or sludge may be composted with straw and other vegetable waste, or with mixed refuse from domestic, commercial or institutional premises.

Two types of composting can be considered: Aerobic and Anaerobic composting (which is in fact a kind of digestion). The latter is the simplest form, as it doesn't need the facilities for aeration. Anaerobic decomposition of organic matter is, however, often associated with the formation of foul smelling gasses such as indol, skatol and mercaptans. The anaerobic composting process usually takes place at temperatures between 8° and 45 °C, with mesophilic micro-organisms.

The aerobic composting process requires a sufficient input of oxygen. In this process, higher temperatures (above 60 °C) can be reached and both mesophilic and thermophilic micro-organisms are involved in the composting process. Research has pointed out that this process of aerated thermophilic composting can provide a high degree of pathogen inactivaton. It produces a well-composted material which has been shown to be a useful and effective soil conditioner (Shuval *et al.*, 1981).

The three general elements of a composting process are:
1. Pre-processing, which can include grinding or shredding and separation of solid inorganic waste. In case of co-composting, this pre-processing ends with the addition of sludge to other organic waste / material.
2. Composting, which is done with windrows, aerated static pile or in-vessel composting.
3. Post processing, which consists of grinding or sieving, de-stoning and other steps to prepare the compost for utilising and marketing (Epstein, 1987).

Windrow

Windrows composting systems are rows from organic waste and nightsoil mixed with ashes or wood chips or domestic refuge. The rows usually have an initial height of 1 to 2 m. with 2 to 4.3 m. at the base. The rows are turned and mixed periodically during the composting period, in order to supply oxygen. During the composting period from about 21 to 28 days a temperature of 55 °C is maintained (Shuval, 1981; Metcalf & Eddy, 1991).

Aerated static pile

The aerated static pile system consists of a grid of aeration or exhaust piping over which a mixture of dewatered sludge and bulking agent (e.g. wood chips) is placed. This system can be seen as modification of the windrow concept. Typical heights are 2 to 2.5 m. Material is composted for 21 to 28 days and is typically cured for another 30 days or longer.

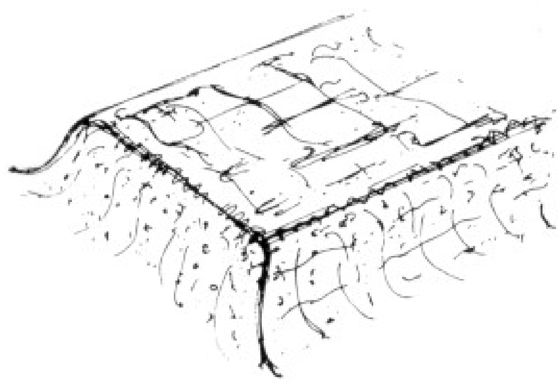

Figure 4.1 A compost windrow (Franceys, 1992)

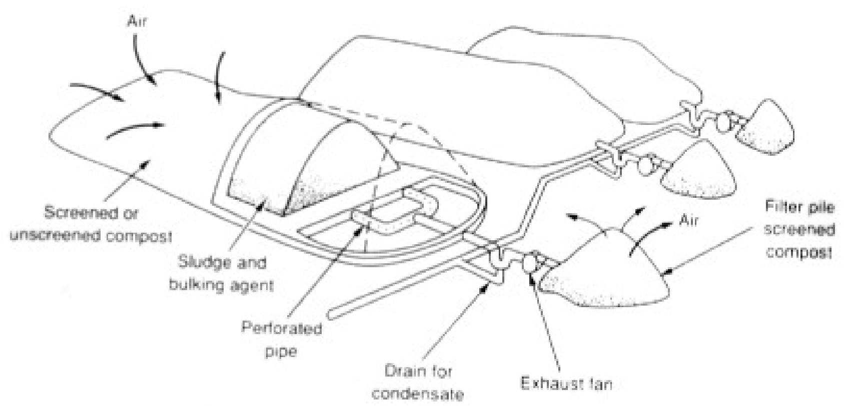

Figure 4.2 Aerated static pile composting system (Metcalf & Eddy, 1991)

Closed or In-Vessel systems

The composting processes takes place inside vessels or containers and have and increased process and odour control, a faster throughput, lower labour costs and smaller area requirements than the systems described above. However, these systems are usually associated with extremely high-cost and complex operation and maintenance problems.

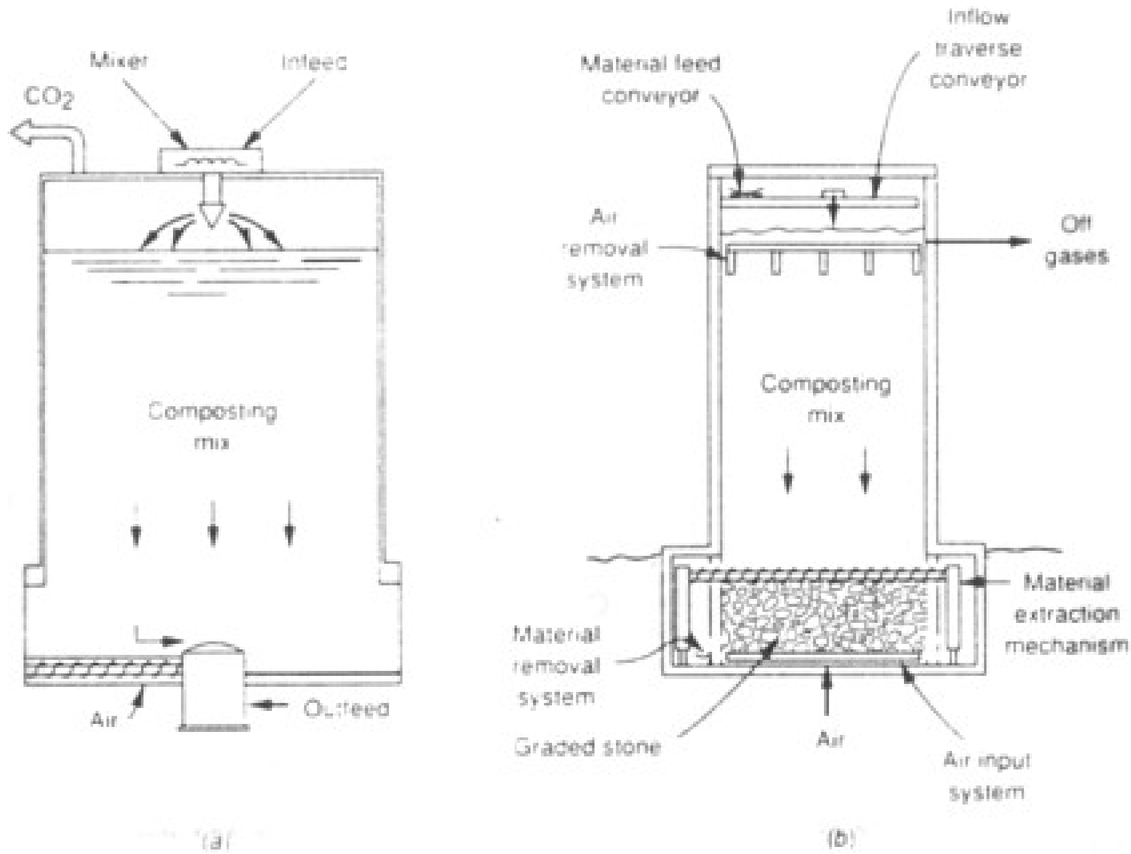

Figure 4.3 In-vessel sludge composting reactors: a) cylinder tower, b) rectangular (Metcalf & Eddy, 1991)

Vermi-composting

Vermiculture is the degradation of organic waste through earthworm consumption, which converts the material into worm castings (Shanthi *et al.*, 1993). The earthworms are employed to convert organic waste into a rich agricultural fertiliser. Worm farming for waste disposal was first employed in the USA in 1830, but only recently the problems with the environmental conditions for the worms (temperature, humidity, pH value of the soil) have been overcome with the discovery of the robust *Dendrabena* earthworm. The worms in the 'machine' digest the organic waste (e.g. sewage sludge) which is fed in layers to the surface of the soil in the 'machine'. For example, the input of 28.5 kg of sewage sludge results in 9.05 kg of saleable fertiliser. The worms also consume metals present in the waste. Test results showed that the worms can not only reduce the waste material by 75%, but also reduce the metal content in the waste by a similar percentage (WEI, 1998).

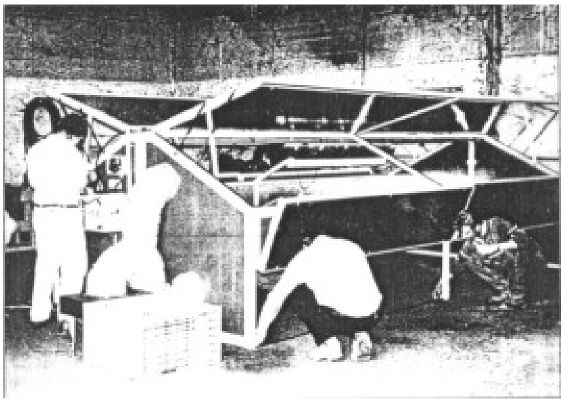

Figure 4.4 The vermicomposting machine (WEI, 1998)

Biological sludge reduction can be achieved by the addition worm treatment step in a wastewater treatment plant. Worms are able to reduce the sludge production of a sewage treatment plant with a considerable percentage (around 10 - 95 %). A positive relation was found between the amount of worms and the sludge production of the treatment plant. In this process the bacteria are ‘eaten’ by the worms. A certain amount of bacteria is converted into a smaller amount of worms. The disadvantage of this process is that the optimal conditions for worms are systems with a low organic loading (up to 0.2 kg BOD/m3·d) (Ratsak, 1998). This means that this procedure might not be appropriate for the treatment of Faecal Sludge, as the concentrations and thus the loading of the treatment systems will exceed the loading rate of 0.2 kg BOD/m3.d. Shanthi *et al.* (1993) concluded that, although worms can survive in various conditions (the moisture range of 20 - 80 % and the temperature range of 20 - 40ºC), worms are unable to survive in unstable organic wastes. This may make the process unsuitable for faecal sludge treatment as FS is usually a rather unstable matter.

4.4.2 (Co-)composting of faecal sludge

Faecal sludge has been used as a fertiliser in Asia for thousands of years. Pathogens, such as bacteria, viruses, protozoa’s and helminths, which are present in the FS, provide a severe health risk for the community. Research pointed out that heat treatment of 55° - 60°C for several hours will assure a total pathogen inactivation, including the most resistant helminth eggs (Shuval *et al.*, 1981). An appropriate way to reach temperatures above 55°C is the composting process. Besides this, composting yields a good organic fertiliser for agricultural uses. After natural or mechanical dewatering the solid fraction of the sludge can further be dewatered using a composting process. A dewatering step is needed before the FS can be composted because the water content of the faecal sludge must be 30 - 60%. If not, the composting process will not take place. The optimum moisture content of the faecal sludge is 50%. Co-composting of nightsoil and organic waste takes place in Korea. It was found that the addition of organic materials (2% by weight) in the form of agricultural waste such as barley straw, rice bran, etc. allowed sufficiently high temperatures (Kim *et al.*, 1986).

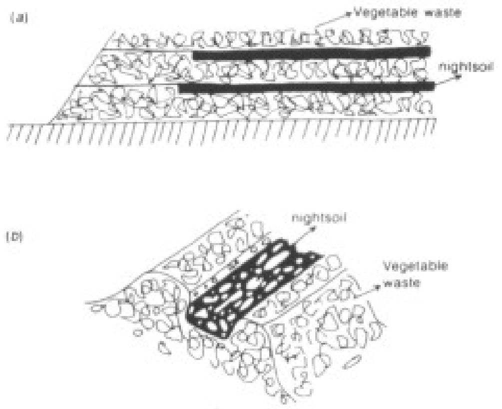

Figure 4.5 Placing nightsoil in a compost windrow (Franceys, 1992)

The nitrogen content of the FS is too high to achieve a complete decomposition. By the mixing of FS and vegetable waste or other types of organic waste and eventually wood chips the C/N ratio can be increased. It has been found that a C/N ratio of 30 is needed for successful aerobic composting. To achieve a good composting process the water content must be less than 60 % in order to achieve a sufficient heat in the compost pile. In the Korean experiments the ratio of nightsoil and organic waste varied from 0.55 to 0.71 based on the weight (Kim *et al.*, 1986). Franceys *et al.* (1992) mentioned that a common method for the composting of FS is to place alternate layers of FS (about 5 cm thick) and vegetable waste (about 20 cm thick) in pits or windrows. Another option is to make trenches in a windrow and fill them up with FS some days after the composting process is started.

Co-composting of sewage sludge is a well-established technology widely practices in Sweden, Denmark, Germany and other European countries. Advantages of co-composting reported by Epstein (1987) based on experiences in North Carolina, USA are:

- Reduced cost of sludge composting by using the solid waste as a bulking agent
- Incorporation of diverse waste streams (sludge, septage, solid waste, yard waste, organic industrial waste)
- Lower capital costs than most alternative technologies
- Combining the cost of sludge and solid waste disposal
- Process flexibility through modular construction
- Reduced volume of mass of solid waste to landfills
- Good environmental control
- A usable, marketable product or products can be produced
- Compatible with recycling

But some disadvantages are mentioned as well:

- A composting facility takes up more space than combustion systems that are often used in the USA.
- Labour requirements are generally high

- Landfill space for solid waste residuals is needed
- A product or products are produced which need to be marketed or utilised

Cases from the USA make clear that co-composting can lead to savings in labour and bulking materials compared to separate processing of solid waste and sludge. Further compared to incineration the operational costs are lower for the co-composting process. Cost analysis from the Korean example showed that the co-composting process was economically viable, even without including the proposed revenue from the sale of the compost (Kim *et al.*, 1986)

4.5 Disposal and discharge

Discharge of sludge into oceans or other water bodies should not be considered as an option, due to the high ecological and public health risks.

A sanitary landfill can be used for disposal of sludge, grease, grit and other solids. Dewatering of sludge is usually required to reduce the volume to be transported and to control the leachate from the landfill. The sanitary landfill is most suitable if it is used for disposal of the other solids wastes of the community, but it is also possible to create sludge mono-fills. After several years, during which the wastes are decomposed and compacted, the land may be used for recreational or other purposes.

4.6 Lagooning

Another method for dumping sludge is lagooning. A lagoon is an earth basin into which untreated or digested sludge is deposited. In untreated sludge lagoons, the organic solids are stabilised by aerobic and anaerobic decomposition, which may give rise to objectionable odours. When it is expected that the percolation water may cause problems the lagoons can be lined or a drainage system can be installed to control the leachate (Metcalf & Eddy, 1991).

CHAPTER 5 WETLANDS FOR SLUDGE TREATMENT

This chapter deals with wetlands as sludge treatment systems that, besides the treatment functions, have options for resource recovery as well. This might, to some extent be the difference with the previous chapter which was focused on treatment processes only.

5.1 Natural wetlands

A definition of wetlands is given by Gosh (1995):

Wetlands are parts of the earth's surface between true terrestrial and aquatic systems. Thus shallow lakes, marshes, swamps, bogs, dead riverbeds, borrow pits, are all wetlands irrespective of their extent and degree of human interventions. Wetlands are generally shallow and thus differentiated from deep waterbodies. Wetlands often include three main components. These are the presence of water, unique soils differing from those of uplands and presence of vegetation adapted to wet conditions.

Natural wetlands are in many developing countries in use for the treatment of domestic and even industrial wastewater. Compared to other wastewater treatment technologies they are a cheap and appropriate solution against water pollution. However, the controlled use of natural wetlands for water pollution may become a problem, especially when the wetlands are used for other purposes, for example as a clean water source. So the use of natural wetlands for wastewater treatment may conflict with important issues as wetland bio-diversity and the sustainable development of natural resources (Denny, 1997). Constructed wetlands may be more controllable alternatives, which are appropriate and may be cost-effective solutions.

5.2 Constructed wetlands

Constructed or artificial wetlands offer all of the treatment capacity of natural wetlands but without the constraints associated with uncontrolled discharging to a natural ecosystem (Metcalf & Eddy, 1991). Artificial wetlands constructed for effluent treatment can either mimic natural wetlands, in the sense that waste waters flow over the surface of the bed and are filtered through dense stands of artificially established aquatic plants, or they can be designed to promote subsurface flow of effluent through the substratum in which the plants are established (Alexander & Wood, 1987). Usually they are designed to achieve plug-flow conditions. Constructed wetlands can be operated at different scales.

Typical aquatic plants can be divided in three groups: emergent, floating and submerged plants. Brix gives a definition of macrophytes:

The larger aquatic plants growing in wetlands are usually called macrophytes. These include aquatic vascular plants, aquatic mosses and some larger algae (Brix, 1997).

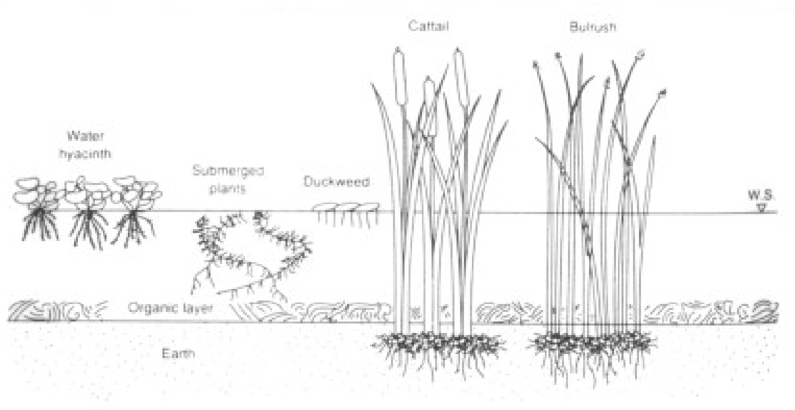

Figure 5.1 Common aquatic plants used in constructed wetlands and ponds (Metcalf & Eddy, 1991)

5.2.1 Emergent macrophyte systems

Sludge drying

All types of emergent macrophyte systems contain at least one species of rooted emergent aquatic macrophyte planted in some type of medium (usually soil, grave, or sand). Research done by Alexander & Wood (1987) indicates that many plant systems e.g. *Typha*, *Phragmites*, and *Scirpus* (*Schoenoplectus*), are capable of not only becoming readily established in the various materials but also grow efficiently and assist in the treatment of the various systems.

Emergent macrophyte systems are, amongst other systems, in use for the dewatering of sludges. The main reason for dewatering of the sludge is that it will decrease the transport and handling costs. Other reasons are that the high water content will be a problem when sludge is used for (co)-composting and also when the sludge is incinerated or disposed of to a landfill.

Reed beds are used for dewatering and mineralisation purposes as reed is expected to improve the treatment performance. The sludge is dried and together with the reed finally turned into compost, which can, for example, be applied as soil amendment or as landfill cover.

The reed bed for the dewatering of sludge is composed of selected media supporting emergent vegetation and the flow path for liquid is vertical. The sludge is spread over the system and accumulates there for a period of considerable period of time - up to 8-10 years (depending on the loading rate, the capacity of the system and the mineralisation rate).
The pollutants are removed through a combination of physical, chemical, and biological processes including sedimentation, precipitation, adsorption to soil particles, assimilation by the plant issue, and microbial transformations (Brix, 1994).

The penetration of the stems of the plants (reed) trough the different layers of sludge maintains adequate drainage pathways, evaporation takes place over the whole reed bed area and the plant contributes directly to dewatering through evapo-transpiration. The root system of the vegetation absorbs water from the sludge, which is then lost to the atmosphere via evapo-transpiration. For European and US conditions it is estimated that during the warm season the evapo-transpiration can account for up to 40 percent of the liquid applied to the bed.

Aerobic conditions in the soil or filter medium are maintained through the combination of root rhizome penetration, oxygen transfer which boosts the population and activity of naturally occurring micro-organisms and the mechanical effect of the tall reeds rocking in the wind. This will result in aerobic conditions on or near the root surfaces in an otherwise anaerobic environment which will enable different complementary microbiological processes to take place in the soil of the reed bed (Reed *et al.*, 1994?). The reeds fed with wastewater or sludge grows rapidly in the nutrient-rich medium and absorbs some of the minerals and water.

Heinss *et al.* (1998) assumes that reedbeds are a feasible treatment option for faecal sludge treatment. Compared to unplanted sludge drying beds, from which require dewatered of dried sludge removal every few weeks or months, the sludge and reeds may have to be removed after several years, as the root rhizome maintains the permeability of the filter and the increasing sludge layer.

Not much is known about the application of reed bed systems for the treatment and resource recovery of the nutrients, organic matter and water present in *faecal sludge*. There is, however, quite some experience with macrophyte systems used for the mineralisation of sewage sludge from activated sludge plants. Sewage sludge is to some extent comparable with faecal sludge as argued in chapter 2. Therefore, examples of sewage sludge treatment may also represent the possibilities for faecal sludge treatment.

Most popular for application in dewatering beds is the common reed (*Phragmites*) which is usually planted in centres of 30 cm. Reed *et al.* (1994?) mention that reed beds are not suitable for the application of raw sludge (and thus not for FS as well) due to the high organic content which will overwhelm the oxygen-transfer capacity of the plants. Strauss *et al.* (1999a), however, report that the treatment of faecal sludge is possible when a ventilation system is installed, which increases the oxygen input into the filter bed.

A design criterion of 2.5 m^2/p.e. for a minimal planted surface is given by Boutin (1987) based on one population equivalent of 40g of BOD_5, 100g of COD and 150 litres (what means that it has a sewage character). Usually an area of 4 - 10 m^2/p.e is used for macrophyte systems for wastewater treatment.

Examples

In many parts of the world reedbeds and macrophyte systems using other emergent aquatic plants are used for the dewatering of sludge. Most experience has been gained in Europe and the US with the application for sewage sludge. It can be expected that these systems can also be applied for FS. Some experiments with reedbeds for the treatment of FS has been done in Thailand (Strauss *et al.*, 1999a). The pilot FS treatment facility in Bangkok has been operated for 18 months. The system is a constructed wetland planted with cattails. The septage or FS is brought on the surface of the filter bed. The percolate is drained and treated in a pond system. The Bangkok's type of septage, used in the experiments, can be characterised as medium strength FS. A solids loading rate of 250 kg TS/m²·yr and a loading frequency of once a week resulted in a significant sludge volume reduction. This TS loading rate is relatively high compared to TS loading rates that are applied in constructed wetlands for sewage sludge dewatering: 100 kg TS/m²·yr, which also means a smaller area requirement per person equivalent. The area requirement of the Bangkok system is 0.03 m²/p.e. (Strauss, pers comm., 1999). The dewatered sludge has a TS content of about 30 %. A suspended solids, COD and TKN removal of ≥ 90 % was achieved. It was concluded that the increase of TS from 2 % to 20 % accounted for the most significant part of the volume reduction. Depending on the final destination (surface water or agricultural uses) the percolate needs further treatment. A schematic presentation of the systems is given in figure 5.2.

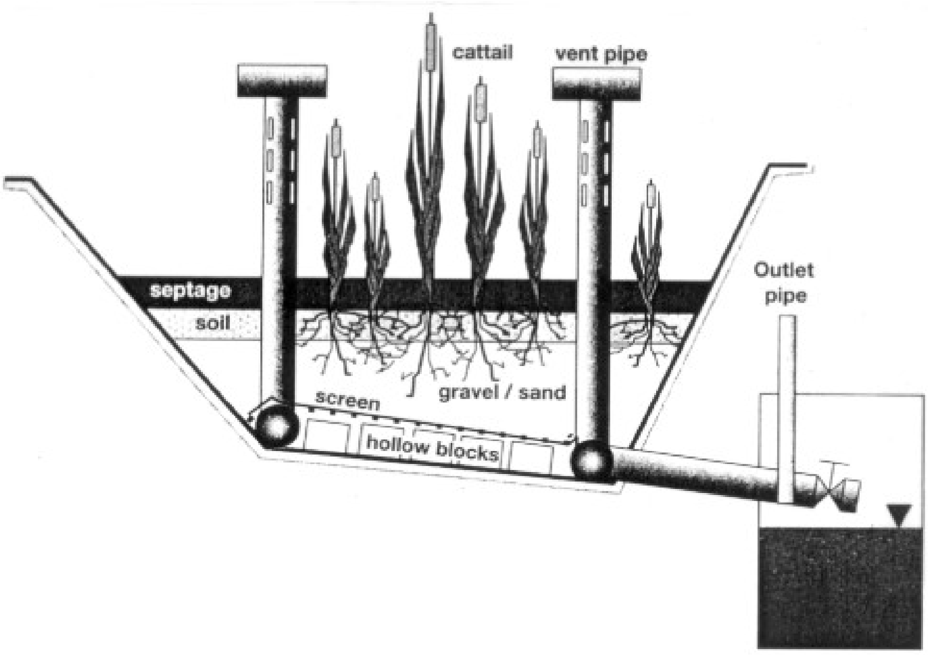

Figure 5.2 Functional sketch of the pilot constructed wetlands loaded with Bangkok's septage (Strauss *et al.*, 1999a)

The M&M/Mars company use a vertical flow reed bed to dewater and compost the bio-solids from the activated sludge plant. Before the sludge is brought onto the surface of the reed bed the sludge is aerobically digested. *The combination of root rhizome penetration, oxygen transfer from the roots and the mechanical effect of the tall reeds rocking in the wind maintains the aerobic, odour free system without operator involvement.* The reed bed removes around 99,5% of the TS content. Data from several reed bed systems in the USA shows that hydraulic loading rates vary from 0.16 m/yr - 0.98 m/yr for anaerobic digested sludge (solids content 2 - 10%), which resulted in a solids loading rate ranging from 13 kg/m²·yr to 60 kg/m²·yr. For aerobic stabilised sludge (solids content 1 - 5%) the hydraulic loading rate ranges from 0.73 - 7.3 m/yr, resulting in a solids loading rate of 16 - 106 kg/m²·yr (Kim and Smith, 1997).

Experiments done in France proved that reeds could contribute significantly to the process of activated sludge dewatering. The drying beds planted with reeds were able to endure sludge loading rates of 44 - 59 kg SS/m²·yr with peak values of around 82 kg SS/m²·yr (Dry matter content of 0.3%). The dry solids content of the mixture of reed and dried sludge is around 11%. This mix can be applied as fertiliser in agriculture and the quality is comparable with

that of sludge dewatered by other devices for small communities (Liénard *et al.*, 1995).
Also in Denmark several reedbeds are in use for the treatment of sludge. In these sludge mineralisation beds, the dry matter is dewatered and mineralised so that the sludge amount ins reduced to 2- 5 % of the original amount. Within two or three weeks the sludge is dewatered, depending on the local climate to a dry matter content of 35 to 48 %. Loading rates of 3 to 20 m3/m2·yr can be applied depending on the dry matter content of the sludge. Every third season, the bed should rest to complete the mineralisation (Transform APS).

Operation

Emergent macrophyte systems (e.g. reedbeds) can be operated in different ways. The two extremes are the horizontal flow system and the vertical flow system. The horizontal flow reed bed, also called root zone system, may be considered as less suitable for the treatment for faecal sludge. It is mainly designed for (waste-) water treatment.

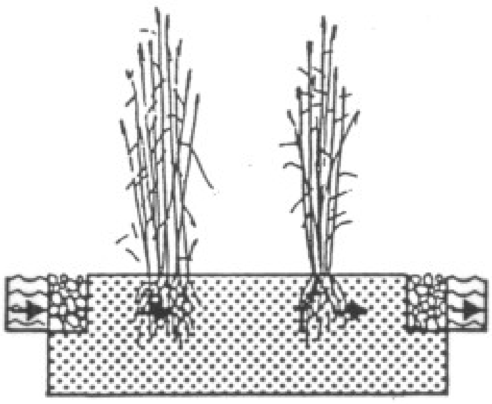

Figure 5.3 Schematic presentation of horizontal flow reedbed

The water is forced to percolate in a horizontal direction through the root zone of the reed bed. Processes as evaporation, microbiological conversion and uptake remove water, nutrients and organic matter by the reed. The application of sludge (especially faecal sludge) in this system may cause the clogging of the system.

The vertical flow reed bed can be compared with a planted sand filter. This type of reed bed is applied for the treatment of wastewater as well as for sludge. The sludge is applied in a thin layer on the surface of the reed bed. The liquids percolate from the top of the filter to the bottom, where it is drained for further treatment or disposal.

The organic matter and nutrients are decomposed and removed by microbiological processes and uptake by the plants. Water evaporates directly from the thin layer on the surface of the reed bed or indirectly via the uptake and evapo-transpiration processes. To achieve an optimal removal (e.g. N-removal) the reed bed is inundated intermittently. By doing this aerobic and anaerobic periods follow each other with the result that aerobic as well as anaerobic processes (i.e. nitrification and de-nitrification) can take place. The presence of macrophytes will also enhance the oxygenation of the filter/reed bed. Reeds and other types of macrophytes such as cattail and bulrush are able to transport air through their hollow stems and roots to the soil.

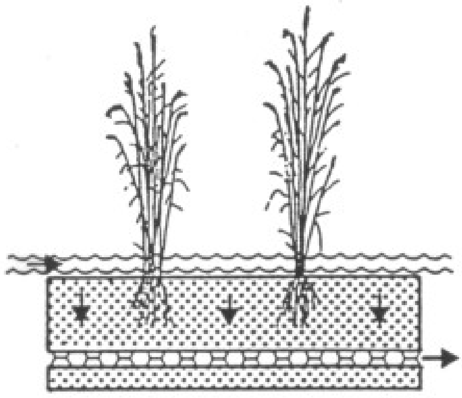

Figure 5.4 Schematic presentation of a vertical flow reedbed

In macrophyte based systems particulate organic matter is removed by sedimentation, filtration and decomposition. The decomposition of dissolved organic matter is done by bacteria, which are present in the soil and in the water. Nitrogen is removed by nitrification and de-nitrification and plant uptake. To provide optimal conditions for nitrification/de-nitrification intermittent inundation can be applied which creates alternatively aerobic and anaerobic conditions. Nitrification is an aerobic process, while de-nitrification is an anaerobic process. Phosphorus is mainly removed by the adsorption to the filter material i.e. the soil, but it is taken up by plants as well. The adsorption rate is determined by the kind of soil (clay will adsorb more phosphorus than sand) and the presence of organic matter, iron or aluminium in the soil. For surface flow wetlands maximum BOD loading rates of about 100 kg BOD/ha·d has been recommended to help prevent the occurrence of mosquito populations (Rowe & Abdel-Magid, 1995).

The efficiency of artificial wetlands is determined by three factors:

1 The substrata responsible for the majority of the nutrient removal capacity through microbiological activity and physic-chemical reactions within the medium.

2 The biotic factors responsible for aeration and enhancing permeability of the substrata.

3 The operational regime imposed on the system: in particular loading rates and retention times.

In temperate climates the plants must be removed before the winter starts, otherwise the nutrients will be released again by decomposition of the plants. In the wintertime there is a nutrient flow from the emergent parts of the plants towards the roots. It is important to remove the plants before this process starts in order to remove the maximum amount of nutrients from the system. So the mowing and removal of the plants will maximise the nutrient removal.

After dewatering in emergent macrophyte systems the sludge needs further treatment. Heinss *et al.* (1998) suggest further treatment in the form of co-composting with organic wastes or further drying prior to direct agricultural use. Also the percolation water from macrophyte systems or drying beds needs further treatment, as in general the nutrient levels in the percolate are too high for discharge into the surface waters. In experiments in Ghana percolate water from drying beds was treated in a series of ponds (i.e. anaerobic, facultative and maturation ponds) (Heinss *et al.*, 1998). Also other wastewater treatment facilities and even direct agricultural application could be considered. The most important reason for the treatment of the percolate water may be pathogen removal.

5.2.2 Free floating macrophytes and fish ponds

In aquaculture systems both floating aquatic plants and fish are produced. These systems are operated with different objectives. In some cases the primary objective is the treatment of wastewater or human excreta. In other cases these systems aim at a high fish or plant production making use of relatively cheap input of resources, i.e. human excreta. Fishponds are mentioned in this paragraph, because often the free floating macrophyte systems and fish production is applied in combination.

Free floating macrophyte systems are usually shallow ponds in which floating aquatic plants are grown. These plants contribute to the removal the removal of water by evapo-transpiration. These systems are also applied for nutrient removal and upgrading of effluents of stabilisation ponds. Floating species such as water hyacinth and duckweed are used. The plants are harvested regularly and after drying, composting or fermentation they can be used as fodder or soil conditioner and fertiliser (Polprasert *et al.*, 1994). Zootech research, New Zealand, has developed a treatment system based on lagoons. In this system algae, zooplankton and seaweed are produced as a renewable source of food in aquaculture (Truman, 1996). There is a limited amount of cultivation of aquatic macrophytes on *human* excreta, mainly vegetables as human food or duckweed as fish seed or other animal feed (Edwards, 1992; p53).

Floating macrophytes (e.g., waterhyacinth) are the plants most commonly used for *wastewater treatment* in tropical and subtropical climates (Reddy & DeBusk, 1987). The reason is the relatively high growth rate and the large nutrient uptake capacity. Water hyacinth is sensitive for a decline in temperature, while duckweed can also be applied in more temperate climates.

Hyacinth ponds

Water hyacinths (Eichornia crassipes) are large, bulbous, floating plants with extensive root systems. Other species can be used in a similar manner to hyacinths, including duckweed (Lemna sp.), water ferns (Azola sp.) and pennywort. Hyacinths are estimated to be one of the most productive photosynthetic plants in the world (growth rate 60 - 110 t/ha·yr), and there are a number of advantages which hyacinth pond systems offer.

- They provide an added level of nutrient removal from the wastewater above that of simple pond systems through the harvesting of the plants themselves.
- Hyacinths incorporated into a treatment pond have the effects of shading the surface, which prevents algae growth, and maintaining a water pH of close to 7.0, which is healthier for the receiving water body into which the wastewater is discharged.
- Hyacinths have the trait of transporting oxygen down their lengths to their root systems, which creates aerobic conditions in much of the area immediately surrounding the roots.
- The root zones of the plants develop into a diverse ecology, which includes bacteria, fungi, predators, filter feeders and detritivors, all of which significantly add to the level of treatment. Optimal depth of the ponds is just greater than the average root depth of the plants, 40 cm. This brings almost all of the wastewater into contact with the roots.

Harvest regimes vary depending on specific objectives of the system. Frequent harvests will remove a maximum of phosphorous, but optimal nitrogen removal comes when the pond is completely covered. The maximum growth rate of the plants is created through frequent harvests, with the pond never being allowed to becoming completely covered. Plants harvested from hyacinth pond systems can potentially be used for animal fodder, but care should be taken regarding heavy metals and other toxic compounds which might be accumulated in the plants as these will be passed on to humans through the food chain. Nitrogen removal in general in hyacinth systems is enhanced due to the nitrification/de-nitrification process. This process naturally takes place whenever there are aerobic and anaerobic conditions next to each other in the presence of organic carbon. This occurs in abundance in hyacinth root zones (as well as in constructed wetland), and nitrogen removal rates of 60-90% have been reported.

The critical design feature of hyacinth ponds, as with all pond systems, is organic loading. The only exception to this is when a hyacinth pond is being designed especially for advanced water treatment, i.e. for nutrient removal. The recommended organic loading rates for various (aerobic non-aerated, aerobic aerated, facultative anaerobic) hyacinth ponds vary from 0.37 kg $BOD/m^2 \cdot yr$ to 11 kg $BOD/m^2 \cdot yr$. Metcalf & Eddy recommend that the organic loading rate in non-aerated hyacinth ponds should not exceed 5 kg $BOD/m^2 \cdot yr$, which is still considerably lower than the loading rates that are applied in macrophyte systems.

The big constraint with the use of hyacinth systems is the temperature requirement of the plant - water temperatures above 10°C are needed with 20-30°C preferred. Another important caution in the use of these plants is their invasive nature in natural ecosystems. If introduced into a warm ecosystem they can rapidly take over and crowd out many native species. (Tad Montgomery)

Duckweed ponds

According to Van der Steen (1998) duckweed ponds are modifications of stabilisation ponds that are covered with a floating mat of small plants, generally called duckweed. Most common species used is *Lemna sp*. The duckweed that covers the pond prevents mixing of the contents of the pond resulting in good conditions for settling of the solids. The duckweed mat also reduces solar radiation penetration, thereby suppressing algae growth. However, the reduced sunlight penetration results in a considerable lower pathogen removal, compared to uncovered ponds.

Organic surface loading of 1.8 - 5.5 kg BOD/m^2·yr can be applied. Several processes remove nitrogen, e.g.: volatilisation of NH_3, nitrification/de-nitrification and sedimentation of particles with organic nitrogen. Both nitrogen and phosphorus can be removed via uptake and harvesting of the biomes.

Under experimental conditions with wastewater growth rates of 0.1 - 0.35 g/g·day have been found (Van der Steen, 1998). Duckweed grown under ideal conditions and harvested regularly has a low fibre content (5 to 15 %) and a high protein content of 35 - 45 %, which makes it a good animal feed. Compared to other aquatic plants duckweed has a high nutritional value and is easy to harvest.

Fish ponds

Aquaculture is the growth of fish and other aquatic organisms for the production of food sources and is used in many places to treat wastewater or nightsoil. In various counties, mainly in Asia, the use of human excreta for the fertilisation of fishponds is a common practice. In China, Taiwan, Hong Kong, Malaysia, Japan and India human excreta is disposed of into ponds or fresh water systems. In West Java, Indonesia 85% of the fish ponds serves as excreta disposal ponds with the use of overhung latrines (Strauss & Blumenthal, 1990a). In rural Indonesia in most cases fish is raised in poly-cultures. Common species are: Tilapia, Nile carp, Java carp, Common carp, Kissing gouramy, Giant gouramy and Sepat siam. But the most common species that are grown are Carp and *Tilapia*. Also there are a few reports of the cultivation of fish in wastewater pond systems in Europe (e.g. Munich) and Africa (Edwards, 1992). The primary goal of human excreta fed fish culture is not always the production of fish, but in many cases the ponds are meant as a sanitary facility with fish production as an important side effect (Strauss & Blumenthal, 1990b).

On the one hand these systems function as a sanitation facility, on the other hand these systems are used to grow fish and vegetables. The human excreta is directly disposed of into the ponds by the use of overhung latrines or it is transported to the aquaculture sites by different means of transport such as carts, barges and sewer systems. Most excreta reuse involves the culture of fish for human food, but in a few places the fish are sold as livestock feed.

For the design of a nigh soil fed fishpond the nutrient loading rates are important. In many cases these data are not available and thus the BOD loading rate will be used instead as an important parameter. Nightsoil loading rates of fishponds vary from 1.5 kg to 16.3 kg BOD_5/ha·day. The maximum of 16 kg BOD_5/ha·day was reported for Java and Taiwan and may approximate the optimal loading rate of night soil into ponds (Edwards, 1992; p140). Nightsoil loading rates of fish ponds reported by different authors are given in table 5.1.

Table 5.1 Nightsoil loading rates in fish ponds (Edwards, 1992)

Country	Quantity of nightsoil added	Loading rate (kg BOD_5/ha·day)
Hong Kong	6.1 ton/ha·month or 0.2 ton/ha·day	4.3
Indonesia	10-20 persons used overhung latrine on 400 m2 pond, or 250 - 500 persons/ha·day	8.1 - 16.2
Malaysia	3.6 - 4.5 m^3/month or 0.12 - 0.15 ton/ha·day	2.6 - 3.3
	7.9 m^3/week or 1.1 ton/ha·day	23.9
Taiwan	up to 205 ton/ha·yr. or 0.75 ton/ha·day assuming 9 month fish-growing season	16.3
Taiwan	38 ton/ha/yr. or 0.14 ton/ha·day assuming 9 month fish-growing season	3.0
Taiwan	4.5 ton/ha 4-6 times in 9 month growing season or 0.07-0.10 ton/ha·day	1.5 - 2.2

In ponds for treatment of (pre-treated) sewage usually higher BOD loading rates are applied. This may be due to the lower BOD concentration in sewage compared to nightsoil or faecal sludge. Table 5.2 gives an example of BOD and Nitrogen loading rates for *sewage*-fed fish ponds.

Table 5.2 BOD and Nitrogen loading rates of sewage fed fish ponds (Edwards, 1992)

	Type of influent	BOD loading rate (kg/ha·day)	Nitrogen loading rate (kg/ha·day)
Oklahoma	domestic sewage	12 - 35	-
Arkansas	clarified sewerage	12 -31	3.4 - 7.8
Israel	wastewater	25 - 45	-
Hungary	settled sewerage	11-12	3.3 - 4.2
China	sewage	20 - 30	-
-	septage	15	5 - 8

Although it is a common practice to use human excreta for fish production in Asia, the use of nightsoil in fish ponds has decreased due to several reasons. The handling and transportation of nightsoil is labour intensive and causes health risks for the workers.

Nightsoil is replaced by chemical fertilisers or livestock manure as a result of:

- rapid industrialisation and increasing labour costs
- the high costs of the transportation of the bulky organic manure
- ready availability and relatively low price of chemical fertilisers, often prescribed by governments
- replacement of nightsoil collection in buckets by sewerage systems
- the intensification of the aquaculture requires more efficient fertilisation and feeding of the ponds

Most of the wastewater treatment achieved in aquaculture systems has been attributed to the bacteria attached to floating aquatic plants. There is little evidence that fish contribute directly to treatment (Metcalf & Eddy, 1991). Some authors reported an increase of the phyto-plankton concentration in waters containing fish; others have found a decrease of the phyto-plankton concentration.

5.2.3 Submerged macrophyte based systems

Not much is known about the treatment capacity of submerged aquatic weeds. The submerged species of macrophytes are considered as not effective for wastewater treatment due to the requirement of light penetration into the water bodies (Poh-eng & Polprasert, 1996).

CHAPTER 6 RECOVERY OF THE RESOURCES FROM WETLANDS

In the industrialised world the use of wetlands are largely directed towards better water quality for the natural environment, the removal of nutrients from effluent of sewage treatment plants and the removal of toxins such as heavy metals from industrial wastewater. In developing countries there are good opportunities for the exploitation of the products and effluents of wetlands, besides the use for the improvement of the quality of usable water and the environment.

Resource recovery from faecal sludge with wetlands has several aspects:

- Direct reuse of the faecal sludge in agriculture or aquaculture
- Reuse of the effluent of treatment systems, such as ponds and wetlands
- Reuse and further treatment of the biomass of the wetlands (i.e. plants, treated sludge)

6.1 Direct reuse of Faecal Sludge

6.1.1 Agriculture

The organic matter and nutrients present in the faecal sludge are valuable products for the application in agriculture. Nutrients such as nitrogen, phosphorus and potassium are essential for plant growth and micro-biological life in the soil. The soil structure is stabilised by organic matter, this is what makes a fertile soil friable, allowing water to drain and oxygen to get to plant roots. Furthermore a well-structured soil contains more plant available water than a poorly structured one, and it is easier for plant roots to grow through a well structured soil. The crops consume the organic matter in the soil and although crop residues return some organic matter, the soils need extra organic matter to maintain them in good condition. So extra organic matter is needed every year to prevent the soil from eroding by wind and water (Evans, 1998).

Faeces, like other organic fertilisers, have long-term beneficial effects on the soil. They amend the soil's organic and humus fraction, an advantage not offered by mineral fertilisers (Visker & Timmer,1998). Compared with other organic fertilisers such as manure, compost and digested sludge, faecal sludge has relatively high nutrient contents. An overview of the nutrient contents of various natural fertilisers is given in Table 6.1.

The use of human excreta as fertiliser in agriculture has proved to be feasible, acceptable and a very ancient practice in some Asian countries. In China, for example, over 90 % of the nightsoil production is applied on the land. This represents one third of all nutrients actually used by the crops (Visker & Timmer, 1998).

Table 6.1 Nutrient values of various natural fertilisers (Cross & Strauss, 1985)

	Nutrient content (% dry solids)		
	Ntotal	P2O5	K2O
Human faeces	5-7	3-5.4	1-2.5
Human urine	15-19	2.5-5	3-4.5
Fresh nightsoil	10.4-13.1	2.7-5.1	2.1-3.5
Fresh cattle manure	0.3-1.9	0.1-0.7	0.3-1.2
Pig manure	4-6	3-4	2.5-3
Plant residues	1-11	0.5-2.8	1.1-11
Composted material	0.4-3.5	0.3-3.5	0.5-1.8
Digested biogas sludge	1.5	1.1	1.1
Septage	~ 5		

It is estimated that during the 50s and 60s, 70-90% of all nightsoil produced in Chinese cities and villages were collected and used as fertiliser in agriculture. Various authors reported application rates of 60-100 tons/ha/year of farm compost and 20-30 tons/ha/year of nightsoil (Cross & Strauss, 1985). Wang (1997) reports that, considering the low cost and high efficiency, one of the most attractive and beneficial options for sewage sludge use in China may still be land application. Figures used by Wang make clear that sewage sludges from China, UK South Africa and US have a considerably lower nutrient content than fresh nightsoil and FS.

Not all land is suitable for the application of faecal sludge or sewage sludge as fertiliser. Criteria for the selection of suitable land for the application of faecal sludge are (Towers & Horne, 1997; Strauss, pers. comm. 1999):

- The risk of groundwater pollution.
- The surface runoff.
- The metal-binding capacity of the soil
- The impact of regulatory changes
- The hauling of non-dewatered sludges might not be sustainable, particularly in large cities.

The direct use of excreta or faecal sludge as fertiliser brings along the potential risk of disease transmission through pathogens. These risks can be minimised by proper treatment before use (e.g. composting) and high levels of personal hygiene (Stauss & Blumenthal, 1990a). Various treatment methods are described in Chapters 4 and 5. Strauss *et al.* (1999b) have suggested guidelines for the application of treated faecal sludge in agriculture (Table 6.2).

Table 6.2 Suggested sludge quality guidelines for reuse of treated faecal sludge (Strauss *et al.*, 1999b)

	Use of treated sludge in agriculture
COD (mg/l)	not critical
BOD (mg/l)	not critical
Helminth eggs (No./l)	3 - 8/ g TS[a]
Faecal Coliforms (No./100 ml)	Safe level if egg standard is met

[a] Based on nematode egg load per surface unit area derived from the WHO guideline for wastewater irrigation, and on manuring rate of 2-3 tons of dry matter/ ha per year.

Guidelines for the application of (un-)treated wastewater for agricultural purposes may also give an indication for the safe use of faecal sludge (see annex 1; WHO, 1989).

6.1.2 Aquaculture

There is little evidence that the fish consumes the excreta what is disposed of into the ponds. It is assumed that the fish feeds on the zooplankton and phyto-plankton, which is growing on the nutrients from human excreta. Feeding patterns of fish are still not fully clear and research shows contradictory effect of the presence of fish on the phyto- and zooplankton population (Edwards, 1992).

It is clear, however, that the fertilisation of fish ponds with human excreta has positive effects on the amount of fish produced. Around 30,000 tonnes per year of tillapia and carp are produced in fresh water ponds receiving human excreta. Cross and Strauss reported from a fish farm in Taiwan which achieved a production of 132 kg/ha·yr and 619 kg/ha·yr in unfertilised and in nightsoil fertilised ponds respectively. Even productivity of more than 1 ton/ha·yr are reported which are not uncommon for well-maintained nightsoil fed ponds in Asia (Cross & Strauss, 1985).

Research in Indonesia pointed out that the application of untreated faecal sludge or night soil poses health risks for the workers and the community. Pre-treatment in a Chinese 3 tank digester system is suggested as a proper pre-treatment facility (Zandstra & Redekopp, 1986).

6.2 Reuse of Faecal Sludge treatment products

6.2.1 Use of the effluent of ponds and wetlands

All over the world there is experience with (treated) wastewater irrigation. Some countries, e.g. Chile and Mexico use effluent for more than 80 % of their irrigation needs (Bartone & Arlosoroff, 1987). In Calcutta, India the effluent of sewage fed fish ponds is used to grow winter paddy (CMDA, 1993). It has been found that the grass carp excretes 72 percent of its diet. The dung is a good fertiliser. In two months 6,800 grass carp can produces 1,650 kg manure per ha, which is enough to fertilise a paddy field (Wang, 1991).

The nutrients in the effluent of duckweed ponds make it possible to avoid using expensive fertilisers. It was estimated that in Israel effluent reuse for irrigation of wheat saves $ 195 per hectare per season (Van der Steen, 1998). It is assumed that the effluent of WSP's, excreta fed fish ponds and sludge drying beds can be reused for irrigation purposes, depending on the crops that are grown. The following effluent guidelines for reuse in irrigation are suggested:

Table 6.3 Suggested guidelines for effluent quality of sludge treatment plants to be used for irrigation (Strauss *et al.*, 1999b)

Reuse [a]	COD (mg/l)	BOD (mg/l)	Helminth eggs (No./l)	Faecal coliforms (No./100 ml)
Unrestricted irrigation [b]	not critical	not critical	1	10^3
Restricted irrigation [c]	not critical	not critical	1	10^5

[a] Irrigation rates and effluent quality standards must be established so as not to exceed the crops' nitrogen requirements (100 - 200 kg N/ha/year depending on the crop)
[b] Irrigation of crops likely to be eaten uncooked, sports fields, public parks (WHO, 1989)
[c] Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees (WHO, 1989)

Although the irrigation with effluent poses an attractive option for cheap fertilisers and probably decreased sludge or wastewater treatment cost, agricultural principles must be taken into account. The nutrient requirements of the crops are not constant throughout the season. Too much nitrogen fertilisation is for instance detrimental for the fruit formation in the latter stages of the growing season (Van der Steen, 1998). Also nutrient requirements differ for each crop. Alfalfa, for example, requires a high nitrogen concentration, while for other crops, such as cotton or grapes (see table 6.4), the optimal concentration is much lower.

Table 6.4 Nitrogen requirements for various crops (Van der Steen, 1998)

Crop	N - requirement (kg/ha·season)
Alfalfa	538
Orange	297
Cotton	200
Grapes (direct consumption)	140
Grapes (wine, Arad)	30 - 60

6.2.2 Use of the biomass of wetlands and ponds

When using constructed wetlands, the harvesting of the emergent plants is not necessary to achieve a significant better treatment performance. (Although the uptake capacity of macrophytes is roughly in the range of 30 to 150 kg P/ha·yr and 200 to 2500 kg N/ha·yr, compared to the loading into constructed wetlands this is not a serious route of nutrient removal. (Brix, 1997)). Research on pilot-scale constructed wetlands have shown that plant uptake was not a significant pathway in the overall N removal (Poh-eng & Polprasert, 1996). Only the plants take up a small part of the nutrients. For example, the N uptake by reed (*phragmites*) is around 3 % of the total N removal of a constructed wetland (Løgstrup, pers. comm, 1998). Plant uptake of nutrients by macrophytes is only of quantitative importance in low loaded systems (Brix, 1997). So the uptake of nutrients by emergent plants is not a significant way to remove nutrients from wastewater or sludge. From this point of view it is not necessary to harvest the plants in order to increase the nutrient removal efficiency. But, when the plants are not harvested, in climates with seasonal fluctuations the nutrients that have incorporated in the plant tissue will be returned to the water by decomposition processes (Brix, 1997). Plant harvesting can, however, affect the treatment performance of wetlands adversely. For instance, the oxygen transfer capacity of wetland plants can be greatly reduced.

There is, however, evidence that floating aquatic plants, such as water hyacinth, duckweed, water peanuts and water lotus can achieve a much higher uptake of nutrients and can therefore contribute significantly to the treatment performance of the system (Wang, 1991; Van der Steen, 1998).

When resource recovery is one of the prime objectives of the treatment system, the plants should be harvested. Resource recovery in this sense is not the maximum removal of organic matter and nutrients out of waste, but the production of valuable material with waste as a resource.

Aquatic plants can be used as animal feeds, soil additives, and pulp and paper, as well as energy sources (Poh-eng & Polprasert, 1996). The productivity of emergent plants is higher than that of terrestrial communities and agricultural crops because they:

- Do usually not suffer from shortage of water (however, shortage of water occurred with FS application wetlands in Bangkok (Strauss, pers.comm. 1999))
- Have high tolerances for fluctuations in environmental conditions
- Show high photosynthetic efficiencies

Data on annual production, growth rate and standing crop data of aquatic plants and agricultural crops are given in annex 2. From these tables can be concluded that for example in southern Mali the total nutrient uptake of the various crops is considerably lower than the nutrient uptake that can be achieved by using macrophytes.

Poh-eng & Polprasert also give an overview of the processes used to convert emergent plants to different possible products:

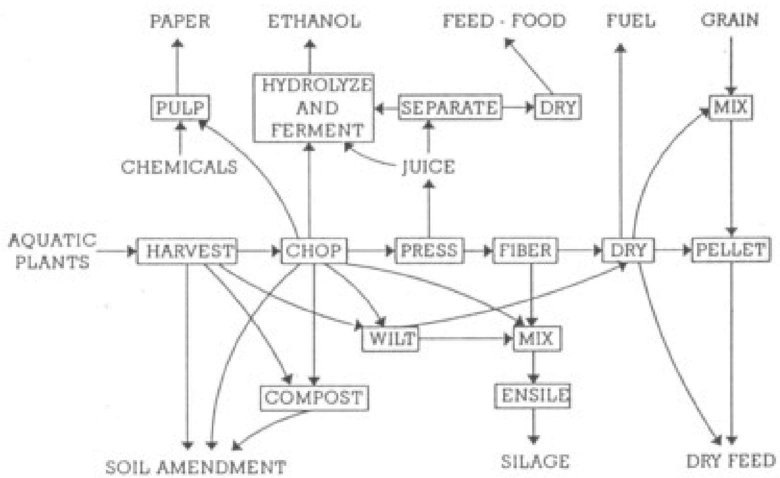

Figure 6.1 Different end products of harvested emergent plants (Poh-eng & Polprasert, 1996)

Six types of uses can be distinguished:

Soil additives

Plants harvested from a constructed wetland treating FS can be turned into soil additives either in the form of mulch and organic fertilisers or by burning the plants to ash or using them to make compost. A composting process under a mixing ratio of dewatered sludge to reed (*Phragmites australis*) from 1:4 to 1:1 on a wet weight basis resulted in compost which exerted a beneficial effect on the growth of rice plants and grain yield (Kurihara *et al.* 1987; in: Poh-eng & Polprasert, 1996). For composting moisture content of 50 - 70 % is required. The relatively high nutrient content in emergent macrophyte plants (see tables annex 2) favours the microbes which produce the compost.

Polprasert *et al.* (1994) did experiments where water hyacinth plants together with pig-manure, leaves and anaerobic digested sludge were mixed and composted. Water hyacinth and pig manure were previously found to have C/N ratios of 20/1 and 8/1, respectively. Because of this, leaves with a C/N ratio of about 60/1 were added to adjust the C/N ratio of the mixture to between 25/1 and 30/1, suitable for microbial mineralisation. The moisture content of the piles was maintained at 60-70 %. The piles were covered with rice straw to prevent heat loss. With the recommended composting period of 30 days, the N and P contents of the compost were 1.9 and 1.2 respectively, based on % dry weight.

An experiment in San Diego, USA with the application of composted sewage sludge on agricultural land pointed out that composted sewage sludge can improve the yields of onion, lettuce and turf. During the two year experimental period the pH of the soil decreased and levels of organic matter, primary nutrients, soluble salts and heavy metals increased. The drawback of the use of the sewage sludge compost is the need to monitor soluble salt levels (Bevacqua and Mellano, 1993).

Energy recovery

Wang (1991) estimates that the carbon fixed by green plants via photosynthesis, when used for energy production, provide a large portion of the total energy consumption in the world. The increasing energy shortage has promoted the exploitation of biological energy as an important energy source. Of various biological utilisation technologies, the most practical one is the conversion of wild plants and agricultural wastes into energy by means of fermentation, mainly in forms of ethanol and methane production (Wang, 1991).

Methane fermentation is the most popular technology for biological energy utilisation in China. In 1991 more than 7 million small digesters were in operation in rural areas, receiving human and animal manure, grain barns and crop stalks, aquatic plants, sewage and wastewater from agricultural produce processing industries for methane fermentation. The total annual production was 720 million cubic metres of methane gas, and some 15 million farmers had access to the methane gas (Wang, 1991). SULABH an international and Indian NGO uses biogas from their public toilets for cooking and lightning (Heinss, pers. comm, 1999).

The carbohydrates, which are for the major part present in the roots and rhizomes of the emergent macrophytes, can potentially be converted to alcohol fuels via hydrolysis and fermentation. The ethanol production out of cattail was found to be comparable with the ethanol production out of corn, sugar-beet and sugarcane (Poh-eng & Polprasert, 1996). The ethanol can be used as an energy source. For instance, ethanol has been produced form agricultural wastes and refuse in Japan, and the produced quantity accounted for 60 % of the total ethanol production in 1988 (Wang, 1991).

Another option for energy production as a form of resource recovery is direct combustion of the plants. The caloric values for many of the emergent macrophytes species are greater than those for the conventional fuel sources such as lignite coal and municipal waste. A prerequisite is, however, that the aquatic plants need to be properly dewatered prior to combustion (Lakshman, 1987, in: Poh-eng & Polprasert, 1996). Possible applications of different types of plants for energy production after wastewater treatment are actually being examined. Examples are Miscantus, Hemp, Willow (*Salix*) and Eucalyptus (Kuiper *et al.*, 1998; Drenth *et al.*, 1997, Perttu & Aronsson, 1995; Sims & Riddel-black, 1996).

In the Netherlands experiments have been done with the co-incineration of dewatered sewage sludge and coal for the electricity production. This method will decrease the costs of the energy production and it saves costs for dumping of the sludge. The problem is however the increased emission of mercury, which is above the accepted levels (Stravers, 1998). Taking into account the high-tech installations, large scale operation and the mercury emissions, this type of reuse may be perceived as unsuitable especially for the small or intermediate scale in developing countries.

Pulp, paper and fibre

Due to their relatively high crude fibre and cellulose contents, common reed (Phragmites) and cattails can be used as a source of paper pulp and fibre. In Romania reeds were converted into pulp to make printing paper, cellophane, cardboard and other products, such as cemented reed blocks and compressed fibreboard, furfural, alcohol and fuel, insulation material and fertiliser (Poh-eng & Polprasert, 1996). Cattail is suitable for paper making although the paper is difficult to bleach. Soft fibres from the leaves of cattail resemble jute and are used in mats, baskets, cane furniture and other woven articles.

Food potential

A problem with the use of aquatic plants as animal feed is the high moisture content, which causes difficulties in processing, transportation and storage. The process of silaging might become very important in humid tropical and subtropical regions where it is difficult to sun dry the plants due to rapid spoilage.

In Thailand, water hyacinth plants generated from ponds treating pig-farm wastewater were on an experimental basis used for silaging. This option was found to be technically and economically feasible to be implemented at farm scale levels. Silaging is a promising technique to produce animal feed from organic solid wastes. The silaging process takes about 20 days. Chopped aquatic weeds can be made into silage by packing them in a silo to create oxygen-free conditions. Silage made from water hyacinth plants alone may not be acceptable to livestock, but the quantity consumed by cattle increases as the level of added carbohydrates (e.g. rice bran, molasses, peanut hulls, cracked corn or dried citrus pulp) is increased. In the Thailand experiments, the water hyacinth plants were mixed with molasses from a distillery, urea or pig manure, to provide the necessary nutrients for the *Lactobacillus* bacteria, which play a crucial role in the process (Polprasert *et al.*, 1994). Optimum compositions of raw materials (wet weight) for silaging were found to be: chopped water hyacinth plants 85 %; molasses 10 %, pig manure 5 %.

The silaging process resulted in a 3 times higher dry matter content (18 % dry weight) for the silaged plants compared with the fresh water hyacinth plants. The crude protein content increased about 7 times to values of 16 %, which is sufficient for use as supplementary animal feed. The crude fibre content decreased 2 fold, while the crude lipid and ash contents increased slightly. Although this silage can be used as animal feed, rice bran or ground corn should be added before feeding to animals, to increase the dry matter content.

Aquatic plants may be used to supplement animal diets. Cattail and bulrush grown in a nutrient rich environment were found to be higher in crude protein and digestible organic matter than those grown in fresh water areas. However they cannot constitute the entire animal diet (Poh-eng & Polprasert, 1996).

Some of the aquatic plants can be used for human nutrition. Cattails were regarded as food plants by Native Americans and have been termed the most useful emergency food source among the wild plants.

Pharmaceutical uses

There is some indication that emergent macrophyte can be used for the production of chemicals which can be relevant for the production of medicines (Lakshman, 1987;in: Poh-eng & Polprasert, 1996).

Building materials

In China efforts were made to use sewage sludge beneficially in many ways. Sewage sludge has been used to make bricks and other building materials (Wang, 1997), although this may not be reported as the most beneficial and attractive option for the Chinese situation.

The annual production of naturally-grown papyrus can be more than 100 tonnes per hectare per year. In constructed wetlands where nutrients are not limiting, this production may be higher. The culms (stems), which are highly valued products, can be used for e.g. thatching, matting and fencing (Denny, 1997).

Poh-eng & Polprasert (1996) report that the common reed has been used for peasant crafts, thatching, fences and windbreaks for centuries. In Mexico, woven cattail leaves coated with plastic resins are made into place mats, building siding and roof tiles which was claimed to be as strong as fibreglass. In the USA some wetlands are harvested for common reed to serve as thatch for roofing, although the quality of reed from treatment wetlands is generally not considered high (Knight, 1997). Reed leaves may serve as or processed into insulating material.

6.3 Integration of treatment and reuse systems

The integration of faecal sludge treatment and the production of the wetlands (biomass, nutrient rich effluent) leads to promising systems in which waste is a valuable source. An example of an integrated production system is given in figure 6.2. This paragraph describes some examples of integrated sludge or wastewater and resource recovery systems. Faecal sludge is not being used in all the examples, but the different cases may give a good indication of the possibilities for integration treatment and resource recovery.

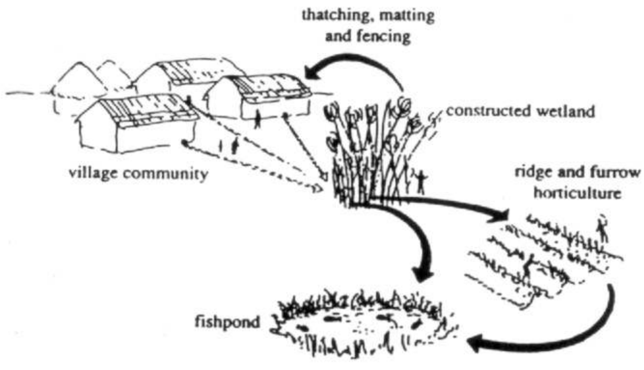

Figure 6.2 Constructed wetland integrated production system (Denny, 1997)

6.3.1 Mali

An integrated faecal sludge and organic waste treatment complex has been planned for Bamako, Mali. Solid waste, which is collected in the municipality, is transported by donkey carts to one of the so called transfer points. From there it will be transported by trucks to the treatment site. As with the solid waste, the faecal sludge will be collected and temporarily stored in the transfer reservoirs and from there it will be transported to the treatment site. The faecal sludge will be subjected to coarse screening before it is treated in a three-pond system consisting of anaerobic, facultative and maturation ponds. Detention periods in the ponds will amount to 3, 15 and 6 days, respectively. Hyacinths will be cultivated in the facultative and maturation ponds and in the storage basin of the treated effluent. The hyacinths float on the pond surface. Their roots absorb nutrients and salts from the ponds water. The bacteria attached to the roots as a biofilm decompose the organic matter. The treated effluent is stored in a reservoir which is subsequently used to irrigate banana trees and the compost windrows. The sludge, which is occasionally drawn from the anaerobic ponds, will be added to the windrows. These windrows are built in successive layers alternating with layers of municipal organic waste mixed with faecal sludge and layers of hyacinth which are harvested from the ponds. The compost and humus will be marketed or used on the banana field (around 1 ha.) which is also included in the project (Diarra, 1998).

6.3.2 Vietnam

Based on many “ancient” already existing systems for recycling human excreta, a concept of integrated rural-urban waste recycling has been developed by Chan (1998). Parts of this whole concept have been realised already in China and Vietnam. The concept is part of the United Nations University (UNU) Zero-emission strategy which is characterised by:

- Total utilisation of natural resources within a closed production system
- Most effective under wet tropical conditions in low-lying and even marshy lands using ingeniously-designed integrated biomass systems
- Biotechnological processes using simple systems and local resources
- Enhanced by natural and simple but appropriate technical means
- Recycling of residues from any process as input for subsequent ones

The human excreta which is generated in the rural environment as well as in the urban environment is composted in decentralised composting plants together with other types of waste, such as treatment sludge, macrophytes and garden refuse. After composting the plastics, can and bottles still present in the compost are separated from the compost and recycled. Leachate from the composting process is digested. The energy produced in the digester unit is applied to heat the composting process. The produced compost is applied in decentralised integrated farms.

6.3.3 India

The Calcutta wetlands in India are conserved as an urban facility for treating the city’s wastewater and recycling it in fisheries and agriculture. The Calcutta wetlands sustain the biggest ensemble of such fish ponds in the world. The area, which is large enough to treat all the sewage of Calcutta, covers about 12,000 ha., of which 3500 ha. comprises fish ponds where fish is grown on sewage. In these ponds the annual fish production is 10,000 tons (Gosh, 1995). The low lying lands east of Calcutta are also partly used for (organic) waste disposal. On the garbage substrate, lying before these ponds vegetables are grown, which are irrigated by sewage that is present in ponds adjacent to the garbage disposal sites. These garbage farms produce about 150 tons of vegetables per day. The effluent of the fish ponds is used to grow winter paddy, resulting in a production of 16,000 tons per year (CMDA, 1993).

Lessons from the Calcutta Wetlands have been used to design wastewater treatment and reuse projects for three onther towns, viz., Bally, Titagarh and Panihati (Gosh, pers.comm., 1999). An example is the Mudialy Fishermen’s Co-operative Society (MFCS) who uses 50 ha. wetland for the treatment of 23 million litres composite sewage per day. Nine smaller ponds are used for the improvement of the water quality before it enters the 6 bigger ponds where fish are grown and further treatment takes place. Besides Carp and Tilapia, species that can endure some toxic stress, more sensitive species were found in the ponds, which is an indication for the level of water quality improvement that takes place. Depending on the water quality of the different ponds fish production rates of 3.5 to 7.8 tonnes/ha·yr are achieved.

Surveys have revealed that these wetlands have a large variety of flora and fauna (Gosh, 1995).

6.3.4 Mexico

An integrated treatment and reuse system for wastewater (SUTRANE) was developed in Mexico in 1970 (Chavez, 1998; Jank, 1995). The entire system can be constructed using local material and labour.

The English translation for Sutrane is Unit Treatment System for the Reuse of Water, Nutrients and Energy at domestic level.

The primary system includes an anaerobic digester for the treatment of **black water** and a two stage reactor for the treatment of **grey water**, a trickling filter followed by a grease trap.
The anaerobic digesters decompose complex organic material, thereby generating methane gas and liberating essential nutrients for plant growth in the secondary treatment system. The methane gas is used as a fuel source for cooking or heating.

Pre-treatment, including the pre-oxygenator, provides film flow on the surface of the rock media, absorbing oxygen necessary to counteract the harmful effect of the detergents. This effluent flows to the grease trap where the oil and grease floats to the surface; the grease is reused for soap production or placed in the anaerobic digesters to enhance digester loading and performance.

Both primary effluents flow into a channel with aquatic plants. These effluents sub-irrigate a secondary filtration field constructed of stone, gravel, and sand with the entire bed placed on an impermeable film. Selected plants are grown on the filtration bed. A multi-purpose greenhouse can be used to provide optimal growth for the plants in both stages of secondary treatment.
The plants in the secondary process consume the available nutrients and, with the assistance of the soil micro-organisms in the filtration bed, provide a relatively high degree of treatment. For larger systems, the Sutrane system concepts have been incorporated into a design referred to as the Dual Microplant system. The components of this system are presented in figure .

Black water combined with the biodegradable organic fraction of **solid wastes** are treated in a 3 stage anaerobic reactor followed by solid/liquid separation and effluent polishing. The selection of the effluent polishing tertiary treatment technology is based on the water quality reuse requirements.

A SUTRANE system treating the wastewater of 2,000 inhabitants showed the following performance: 92.3 % BOD removal , 99.8 % oil and grease removal, 99.4 % organic N removal and 73.5 % total suspended solids removal (Jank, 1995).

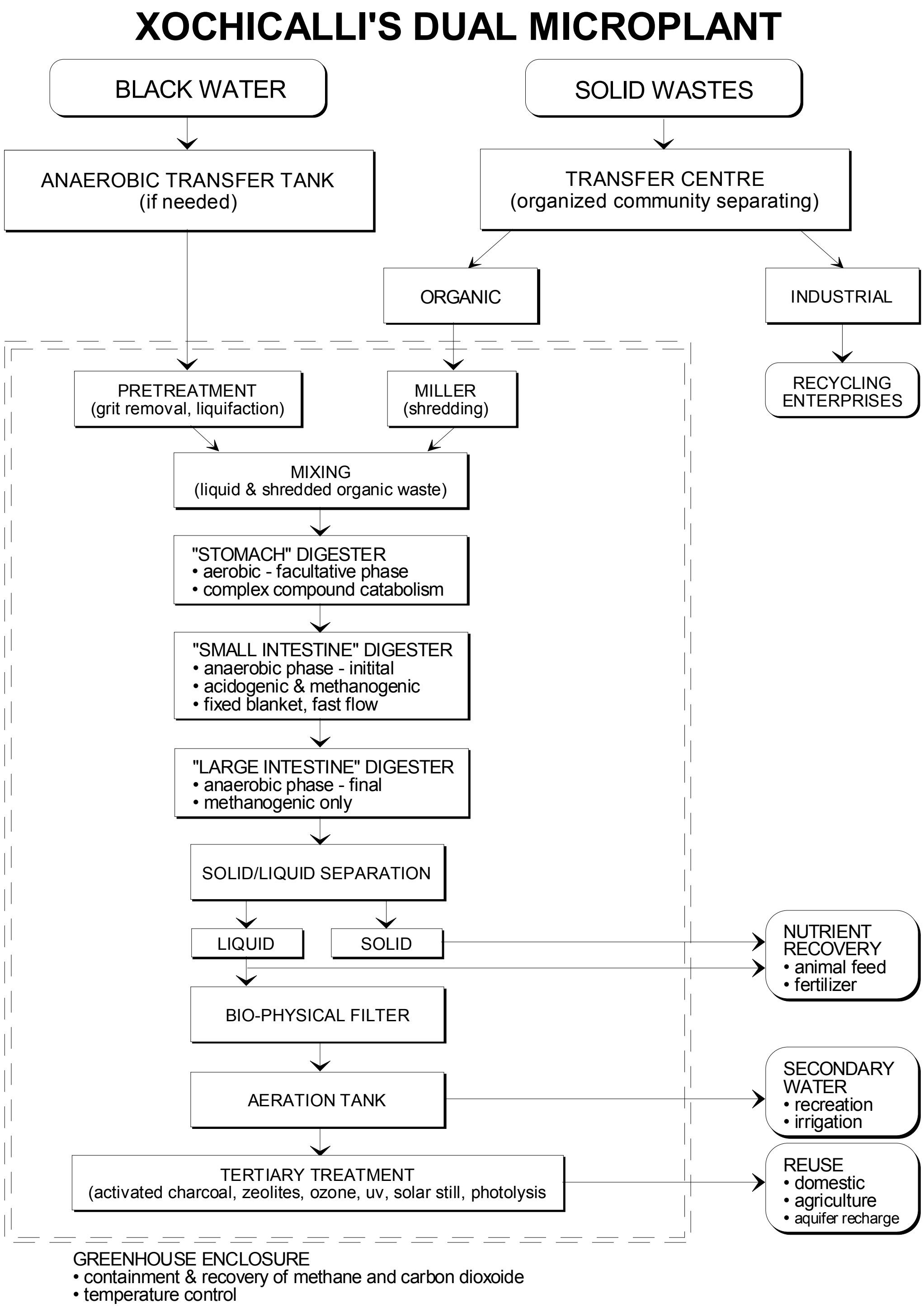

Figure 6.3 Schematic presentation of the processes that take place in a Dual microplant (Jank, 1995)

Chavez (1994) reported the following removal percentages for Dual Microplant systems: Faecal coliforms 93 %, BOD 90 %, COD 85 % and TSS 86 %. The SUTRANE system has already been used successfully in approximately 10,000 applications in Mexico, Central and South America and the Caribbean (Jank, 1995).

6.3.5 Bangladesh

In Mirzapur, Bangladesh experiments have been done with sewage fed duckweed ponds. The effluent of the duckweed ponds was disposed of into the river and the duckweed was harvested and fed to fish that were grown in other ponds. Duckweed is a good animal feed due to the high protein content (up to 30 - 40 % (Sunwater, 1991?). The protein production per hectare is higher than the protein production that can be achieved by cultivating e.g. Alfalfa. A limitation of duckweed is that they can be blown onshore by winds. Also, there are still some economic and marketing problems to be solved (Strauss, pers.comm.1999). In the Mirzapur case a high fish production could be reached, which generated an income of about 3,500 US$/ha·yr (Gijzen, 1999).

Some small communities followed this example and created a sanitary pond with overhung latrines in which duckweed is grown. Other ponds are used for fish production and washing and bathing. In this way a proper sanitary facility has been combined with increased hygienic conditions and income generation through fish production.

6.3.6 China

Wang reports of a variety of eco-systems that integrate sanitation and agricultural production. For example, methane digesters are the central link in the recycling eco-system in Beijing, China. After harvest, grain is sent to processing plants, where bran and straw, once mostly wasted, are converted into fodder for beef cattle, cows, chickens and other farm animals. The animals manure or dropping and remaining straw are fed into digesters. The digested sludge of digesters can not only fertilise the farmland and ponds, but if properly processed they also become a good fodder. The supernatant from the digesters is used for the production of e.g. fish and mushrooms. Also sludge from fish and lotus root ponds is used as fertiliser. The leaves of vegetables and mushroom dregs are also fed to animals (Wang, 1991).

Another example is a recycling eco-system for comprehensive wastes treatment and utilisation. This ‘system’ is capable to treat and reuse high strength wastewater. After methanic fermentation, most organic loading is converted into biogas, resulting in a low Biochemical and Chemical Oxygen Demand (BOD/COD) concentration in the effluent (supernatant). The biogas serves as a clean fuel for cooking and heating in farmers’ houses and pr the production activities in enterprises. The digested sludge from the digesters is sent to farmlands, grasslands and forests, where it is used as organic fertiliser with a high content of available nutrients. It is also used as high protein fodder for pigs, chicken and fish. The domestic sewage and the supernatant from the digesters are combined and sent to ponds systems usually consisting of facultative ponds with hydrophytes, duck / geese ponds and lotus or reed ponds. The settled sludge is applied as organic fertiliser. The agricultural products are sent to communities for domestic consumption and to processing factories as raw materials (Wang, 1991).

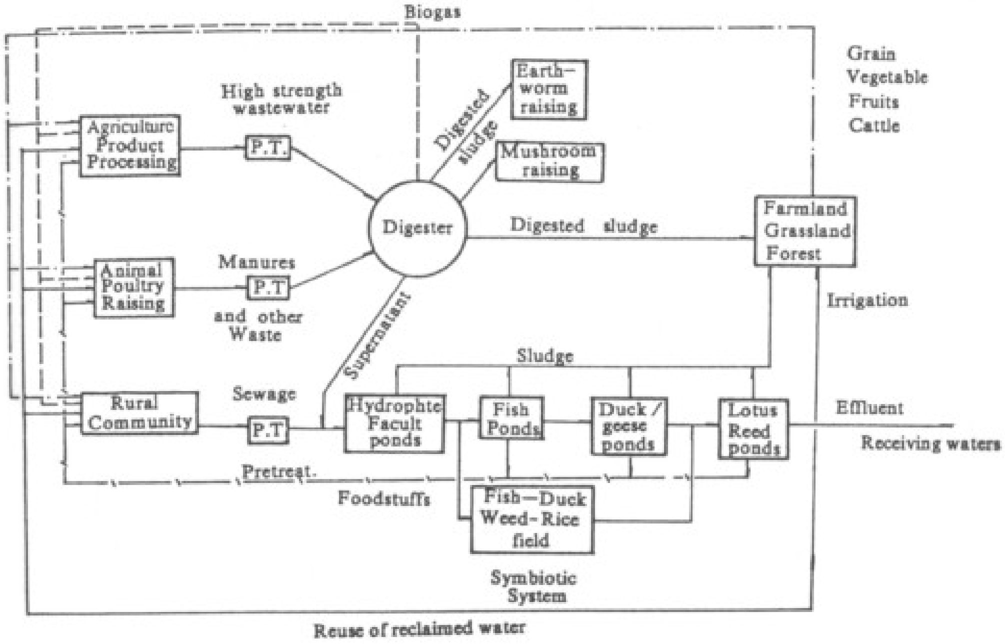

Figure 6.4 Schematic chart of a recycling eco-system for comprehensive wastes treatment and utilisation in rural areas (Wang, 1991)

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

Scope of this research

This research has a general, technical scope. Not much attention has been paid to the economic, institutional, social and cultural aspects of resource recovery from faecal sludge. Different from the technical aspects, these aspects are, however, much more situation-specific. In order to get a better view of the viability of FS treatment and resource recovery systems, case studies should be carried out in which all aspects are taken into account.

Scale of treatment and resource recovery

Faecal sludge treatment making use of wetlands can be operated at different scales. Not much information has been found on the economies of scale of faecal sludge treatment and resource recovery. Further research will give a better view of the most appropriate scale for various situations.

The use of wetlands for faecal sludge treatment

There is not much 'real life' experience with the treatment of faecal sludge in constructed wetlands. There is still a need for further research on specific design parameters and applications of CWs for faecal sludge treatment, although experiences with wetlands for sewage sludge treatment do give a positive indication of their applicability.

Benefits of resource recovery from faecal sludge

In order to quantify the benefits of resource recovery from faecal sludge making use of constructed wetlands, general mass balances for C, N and P would be useful. This massbalances must be set up for two situations:

- treating FS other than by wetlands and making use of C, N and P in the respective solid and liquid end products,
- versus recovering C, N and P from the treated FS and from plants produced with it.

A schematic presentation of the processes that take place in wetlands is given in Annex 3.

Information on integrated systems

In this report some examples of integrated waste(water) treatment and reuse system have been mentioned. There is, however, not much data available describing the exact outline, designs and performances of these systems. This does not mean that integrated systems are mere concepts that are only in the minds of people; in many places integrated systems are in operation. The constraint for the widespread implementation of integrated systems may be lack of data. This calls for research on design guidelines (in the broad sense) and descriptions of existing systems.

Link between different municipal systems

There are several links between the water supply, sanitation and solid waste management sectors which will affect the viability of each individual system. Within the context of Integrated Sustainable Waste Management (ISWM) it is important to get a better view on the possibilities to link different municipal services with each other.

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ANNEX 1

Table A1.1 Recommended microbiological quality guidelines for wastewater use in agriculture [a,b]

Category	Reuse conditions	Exposed group	Intestinal nematodes [c] (arrhythmic mean no. of eggs per litre[d])	Faecal coliforms (geometric mean no. per 100 ml[d])
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[e]	workers, consumers, public	≤ 1	≤ 1,000[d]
B	Irrigation of cereal crops, industrial crops, fodder crops pasture and trees[f]	workers	≤ 1	no standard recommended
C	Localised irrigation of crops in category B if exposure of workers and the public does not occur	none	not applicable	not applicable

[a] from: WHO (1989)

[b] In specific cases, local epidemiological, socio-cultural and environmental factors should be taken into account, and the guidelines modified accordingly

[c] *Ascaris* an *Trichuris* species and hookworm

[d] During the irrigation period

[e] A more stringent guideline (<200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact

[f] In the case of fruit trees, irrigation should cease two weeks before fruit is picked, an no fruit should be picked off the ground. Sprinkler irrigation should not be used

ANNEX 2

Table A2.1 Annual productivity of selected plants (Poh-eng & Polprasert, 1996)

Species	Rate of net production (t dry matter $ha^{-1}.year^{-1}$)	
	Above ground`	Below ground
Arundo donax	12-38	-
Chyperus payrus	30-50	-
Distichlis spicata	7-15	4-14
Juncus roemerianus (Rush)	17-34	1-13
Phalaris arundinacea	8-20	-
Phragmites communis (Reed)	15-35	1-14
Saccharum spontaneum	15-40	-
Scirpus americanus (Bulrush)	4-9	4-18
Spartina alterniflora	5-22	1-8
Typha latifolia (Cattail)	11-33	14-26

Table A2.2 Growth and nutrient (N and P) contents of selected macrophytes (Reddy & DeBusk, 1987)

Plant	Biomass		Tissue composition	
	Standing crop t (dw) ha^{-1}	Growth rates t ha^{-1} yr^{-1}	N g/kg	P g/kg
Floating macrophytes:				
Eichhornia crassipes (water hyacinth)	20.0 - 24.0	60 - 110	10 - 40	1.4 - 12.0
Pistia stratiotes (water lettuce)	6.0 - 10.5	50 - 80	12 - 40	1.5 - 11.5
Hydrocotyle sp. (pennywort)	7.0 - 11.0	30 - 60	15 - 45	2.0 - 12.5
Alternanthera sp. (alligator weed)	18.0	78	15 - 35	2.0 - 9.0
Lemna spp. (duckweed)	1.3	6 - 26	25 - 50	4.0 - 15.0
Salvinia spp.	2.4 - 3.2	9 - 45	20 - 48	1.8 - 9.0
Emergent macophytes:				
Typha (cattail)	4.3 - 22.5	8 - 61	5 - 24	0.5 - 4.0
Juncus (rush)	22.0	53	15	2.0
Scirpus (bulrush)			8 - 27	1.0 - 3.0
Phragmites (reed)	6.0 - 35.0	10 - 60	18 - 21	2.0 - 3.0
Eleocharis (spike rush)	8.8	26	9 - 18	1.0 - 3.0
Saurus cernuus (lizard's tail)	4.5 - 22.5	--	15 - 25	1.0 - 5.0

Table A2.3 Standing crop (storage) of nitrogen and phosphorus and rate of plant uptake for selected aquatic macrophytes (Reddy & DeBusk, 1987)

	Nitrogen		Phosphorus	
Plant	storage kg ha^{-1}	uptake kg ha^{-1} yr^{-1}	storage kg ha^{-1}	uptake kg ha^{-1} yr^{-1}
Floating macrophytes:				
Eichhornia crassipes (water hyacinth)	300 - 900	1950 - 5850	60 - 180	350 - 1125
Pistia stratiotes (water lettuce)	90 - 250	1350 - 5110	20 - 57	300 - 1100
Hydrocotyle sp. (pennywort)	90 - 300	540 - 3200	23 - 75	130 - 770
Alternanthera sp. (alligator weed)	240 - 425	1400 - 4500	30 - 53	175 - 570
Lemna spp. (duckweed)	4 - 50	350 - 1200	1 - 16	116 - 400
Salvinia spp.	15 - 90	350 - 1700	4 - 24	92 - 450
Emergent macophytes:				
Typha (cattail)	250 - 1560	600 - 2630	45 - 375	75 - 403
Juncus (rush)	200 - 300	800	40	110
Scirpus (bulrush)	175 - 530	125	40 - 110	18
Phragmites (reed)	140 - 430	225	14 - 53	35

Table A2.4 Crop data selected for southern Mali (Van der Pol, 1992)

	Yield (kg/ha)	Total nutrient uptake (kg per 100 kg yield)				
Crop		N	P	K	Ca	Mg
Millet	835	4.50	0.50	5.20	0.95	0.95
Sorghum	739	2.60	0.50	3.50	0.70	0.50
Maize	1731	2.50	0.44	2.10	0.50	0.45
Rice	1731	2.40	0.36	2.50	0.50	0.25
Cotton	1307	2.80	0.50	2.40	0.90	0.42
Ground-nut	644	5.20	0.40	2.50	1.00	0.85
Cow pea	400	8.74	1.06	8.25	5.54	1.22
Other crops	51	4.50	0.50	5.20	0.95	0.95
Fallow	2000	1.10	0.20	1.30	0.70	0.30

ANNEX 3

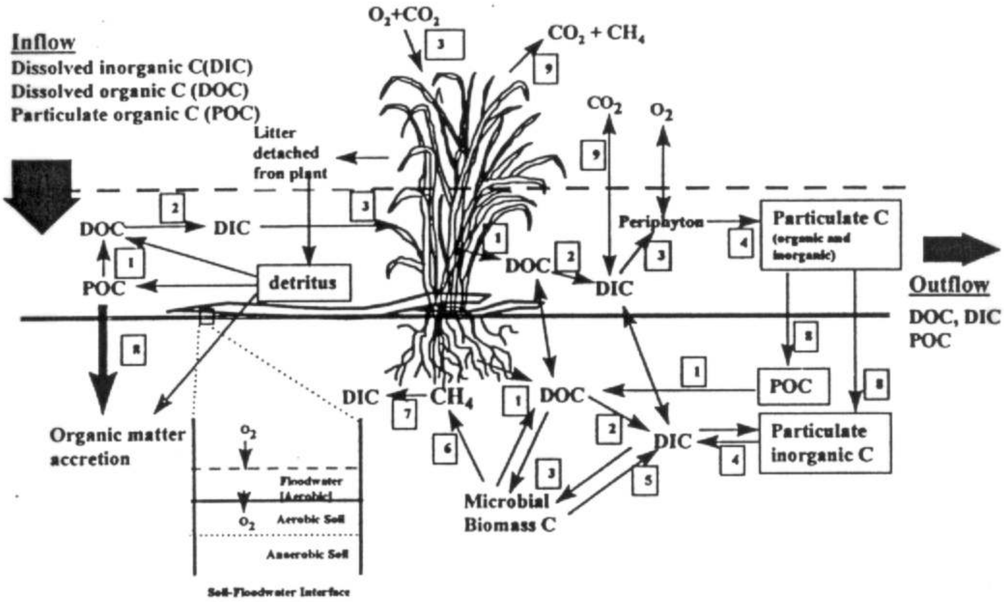

Figure A3.1 Carbon transformations in the soil and water column of wetlands [1) fragmentation and leaching, 2) mineralisation, 3) plant/microbial uptake, 4) precipitation and solubilisation, 5) respiration, 6) methanogenesis, 7) methane oxidation, 8) burial, 9)volatilisation] (Reddy & D'Angelo, 1997)

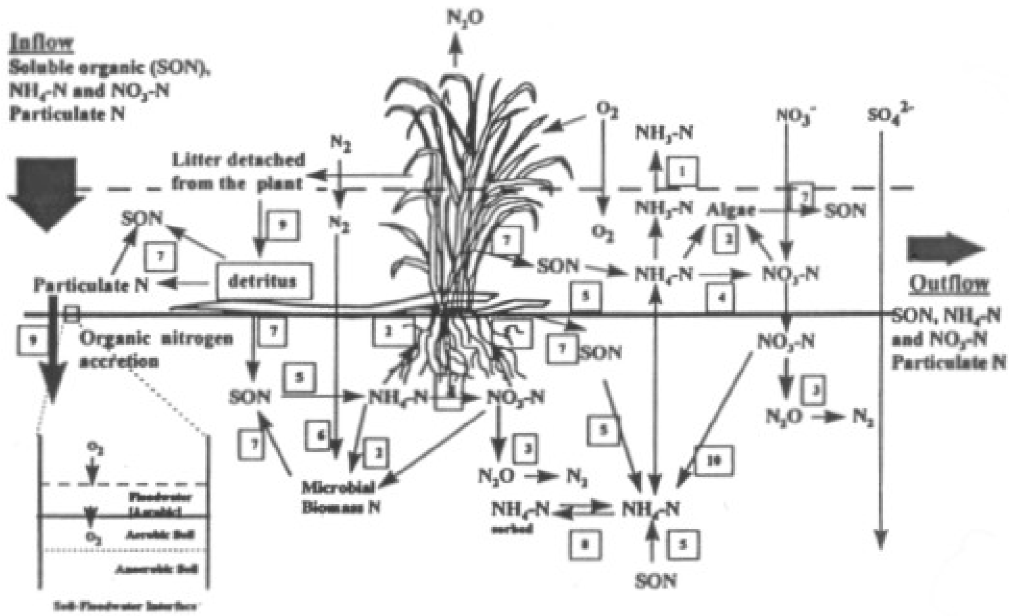

Figure A3. 2 Nitrogen transformations in soil and water column of wetlands. [1) volatilisation, 2) plant and microbial uptake, 3) denitrification, 4) nitrification, 5) mineralisation, 6) nitrogen fixation, 7) fragementation and leaching, 8) sorption and desorption, 9) burial, 10) nitrate reduction to ammonium] (Reddy & D'Angelo, 1997)

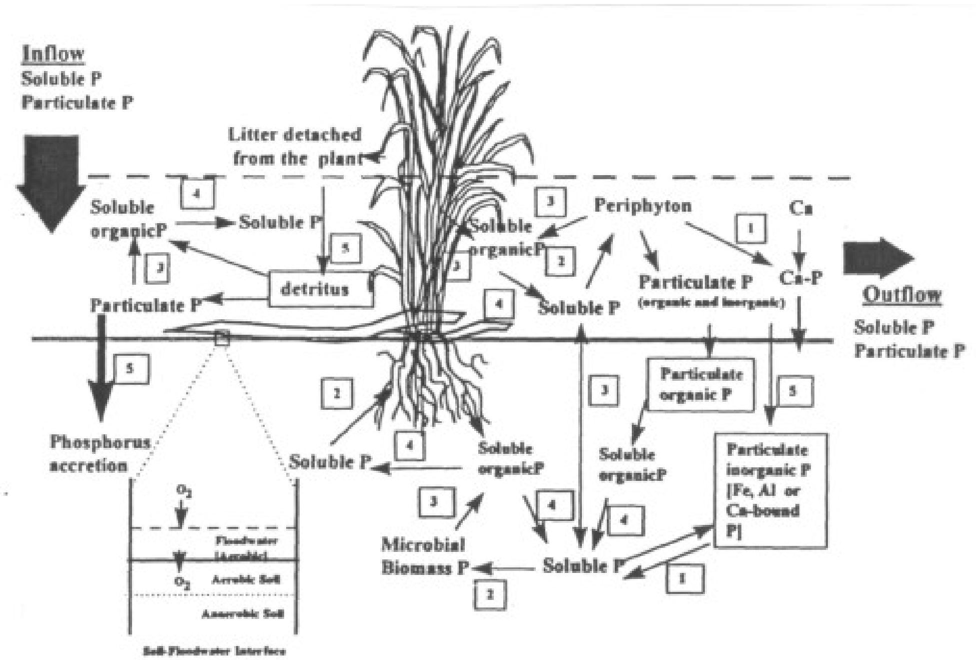

Figure A3.3 Phosphorus transformations in soil and water column of wetlands. [1) adsorption and desorption, 2)plant and microbial uptake, 3) fragementation and leaching, 4) mineralisation, 5) sedimentation and burial] (Reddy & D'Angelo)