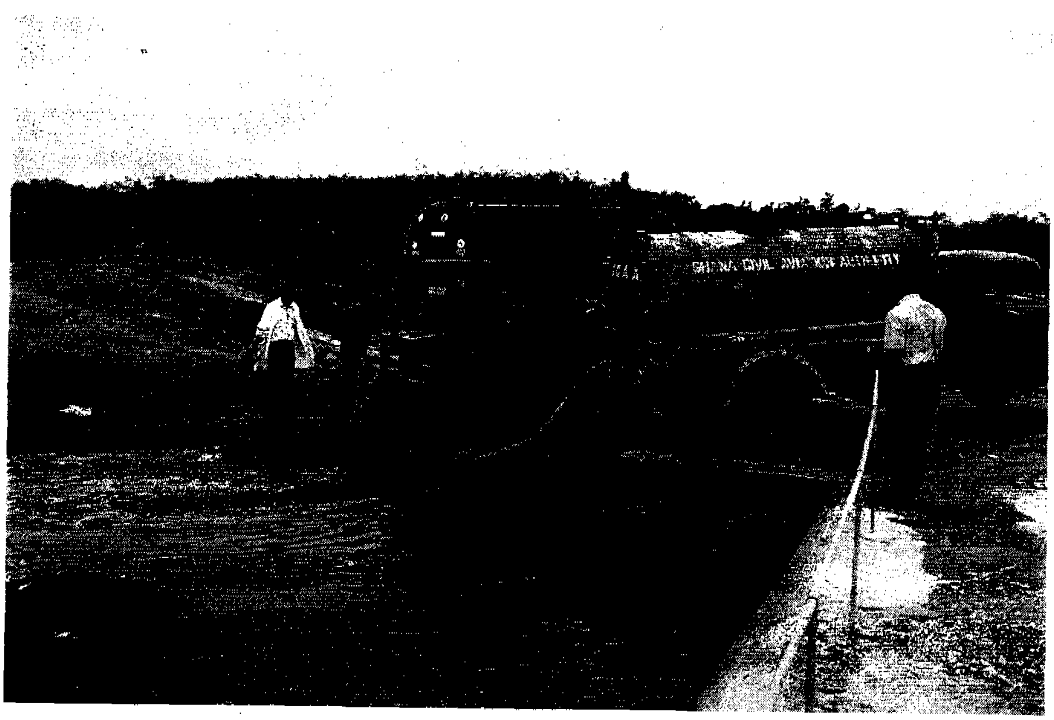
SANDEC Report No. 5/98
Second Edition

Solids Separation and Pond Systems for the Treatment of Faecal Sludges in the Tropics

Lessons Learnt and Recommendations for Preliminary Design



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Solids Separation and Pond Systems

For the

Treatment of Faecal Sludges In the Tropics

Lessons Learnt and
Recommendations for Preliminary Design

Udo Heinss *, Seth A. Larmie **, Martin Strauss *

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Foreword to the Second Edition

The production of a second edition of this publication was initiated as the first print prepared in December 1997 became exhausted. On this occasion, a number of amendments were made. We also eliminated printing errors, unclear formulations and obvious mistakes. We are grateful to those who have carefully read the first edition and provided us with their comments.

The reader may be particularly interested to know that the following additions were made:

- Information on factors influencing faecal sludge (FS) characteristics (Chpt. 2)
- Comparative figures on septage characteristics in Manila, Bangkok and in the U.S.A. (Chpt. 2)
- Information and discussion on heavy metal contents of FS as compared with EU sludge tolerance values (Chpt. 2)
- Effluent quality guidelines for COD and BOD in filtered samples (Chpt. 3)
- Expanded calculations and presentation of design figures on specific land requirements for selected FS treatment options, based on the design example (Annex 2).

Duebendorf/Accra, July 1998

Udo Heinss
Seth A. Larmie
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Abstract

The report sets out to provide guidelines for the preliminary design of faecal sludge treatment schemes comprising solids-liquid separation and stabilisation ponds. The document is based on the results of collaborative field research conducted by the Ghana Water Research Institute and SANDEC on full and pilot-scale faecal sludge (FS) treatment plants located in Accra, Ghana. Published and unpublished documents relating to the subject were also reviewed and taken into consideration in the discussion and recommendation of specific options.

The authors first inform on faecal sludge quantities and characteristics. Faecal sludges may be divided into two different categories, viz. low-strength sludges (septage in most cases) and high-strength sludges (as collected from bucket latrines and unsewered public toilets). Effluent and solids quality standards for faecal sludge treatment plants are discussed and a set of guideline values proposed. The document then proceeds to discuss results of field research conducted on FS pretreatment; i.e., solids-liquid separation in sedimentation /thickening tanks and dewatering/drying beds. Solids-liquid separation in sedimentation units prior to the pond system has been found to contribute to considerable land saving. Further to this, it is likely to lead to simpler pond operations as compared to schemes where solids-liquid separation is integrated in the primary pond. Separated solids were found to accumulate at a rate of 0.15 - 0.2 m^3 per m^3 FS in settling+thickening tanks which are batch-operated at cycles of several weeks. Accumulation in primary ponds which are emptied once every year, may amount to 0.13 - 0.17 m^3 per m^3 FS, approximately.

A main chapter discusses anaerobic pond technology and the results of field investigations conducted with anaerobic ponds. Use of facultative ponds is also described, with special focus on ammonia toxicity for algae from high ammonium levels in fresh and highly concentrated faecal sludges.

A listing of researchable questions and suggested further field studies relating to the treatment options dealt with in this document is also provided.

Schemes providing solids-liquid separation in primary settling tanks followed by liquid treatment in anaerobic and facultative ponds are recommended by the authors as one suitable technical option for treating low to medium-strength sludges such as septage or septage mixed with public toilet sludge. Guidance on the preliminary design of such schemes is provided. Special attention should be paid to potential ammonia toxicity for algae. The gross surface area required for such a scheme amounts to 0.07 m2/cap, including drying bed treatment of the separated solids.

Particular problems may arise when having to treat high-strength, fresh and largely undigested sludges typical of bucket latrines and unsewered public toilets. These hardly lend themselves to solids-liquid separation. High ammonia levels may also inhibit the anaerobic stabilisation process either in anaerobic ponds or in digester tanks.

Keywords: Faecal sludge, septage, public toilet sludge, ponds, sedimentation, thickening, sludge drying beds, anaerobic ponds, facultative ponds, loading rates, ammonia toxicity, design, on-site sanitation

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Acronyms, Abbreviations and Glossary

Acronyms

AIT	Asian Institute of Technology, Bangkok, Thailand
EAWAG	Swiss Federal Institute for Environmental Science & Technology, Duebendorf, Switzerland
EU	European Union
SANDEC	Dept. of Water & Sanitation in Developing Countries at EAWAG
WRI	Water Research Institute (Council for Scientific and Industrial Research, CSIR), Accra, Ghana (formerly Water Resources Research Institute, WRRI)

Abbreviations

BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
FC	Faecal coliforms
FS	Faecal sludge
FSTP	Faecal sludge treatment plant
NH_4-N	Ammonium nitrogen
NH_3-N	Ammonia nitrogen
R + D	Research and development
SS	Suspended solids
STP	Sewage treatment plant
TKN	Total Kjeldahl nitrogen
TS	Total solids
TVS	Total volatile solids
VSS	Volatile suspended solids
WSP	Waste stabilisation ponds
WWTP	Wastewater treatment plant

Glossary

Faecal sludge	Sludges of variable consistency collected from so-called on-site sanitation systems; viz. latrines, non-sewered public toilets, septic tanks, and aqua privies
Septage	Contents of septic tanks (usually comprising settled and floating solids as well as the liquid portion)
Public toilet Sludge	Sludges collected from unsewered public toilets (usually of higher consistency than septage and biochemically less stabilised)
Percolate	The liquid seeping through a sludge drying bed and collected in the underdrain

Acknowledgements

It would not have been possible to prepare this document without the dedicated and persevering efforts of a large number of staff of the Water Research Institute (WRI) in Accra, especially William Duodu, Chief Technical Officer, and his team of able technicians of the Environmental Chemistry Laboratory. Their challenging task, often unpleasant, comprised sampling and analyses of faecal sludges from various points of the treatments systems, including from the trucks delivering raw sludges to the plants. They often spent entire days at the treatment sites in the heat and humidity of the tropics. Isaac Hodgson, sanitary engineer, played a crucial role in planning and supervising the field experiments and in analysing field data.

Collins Annoh, previously with the UNDP/World Bank Water and Sanitation Programme and now private consultant in Accra, provided valuable coordinating support in liaising between SANDEC, WRI and Accra's Waste Management Department. The department is responsible for the management of the city's faecal sludge treatment plants. The WRI/SANDEC field research team greatly profited from Collins Annoh's knowledge and experience acquired from planning and implementation of Ghana's first faecal sludge treatment systems in the late 1980s. He may, therefore, rightly be regarded as Ghana's first leading expert in faecal sludge treatment.

Our appreciation and sincere thanks go to Georgios Alexiou, Allan Batchelor, Isabel Blackett, Ato Brown, Ana María Ingallinella, Duncan Mara, and Warren Pescod, who provided detailed written critiques of the draft. Their comments were very valuable and allowed us to take a refreshed view of the document after we had been engulfed in writing and amending for quite some time. Although most of the reviewers' suggestions were taken into consideration in the final document, we assume full responsibility for the contents of the report.

We are greatly indebted to Sylvie Peter, SANDEC's translator, for the linguistic revision of the document. We also thank H.R. Siegrist and Jack Eugster from the Dept. of Engineering Sciences, EAWAG, who advised us on various aspects of sludge treatment and monitoring.

The field investigations on which this report is based were supported by a grant from the Swiss Development Cooperation.

Preface

SANDEC's Project on Faecal Sludge Treatment

Most urban dwellers in developing countries use on-site excreta disposal systems, such as public and family latrines, aqua privies and septic tanks. In most African and Asian cities, only small sections are serviced by conventional sewerage systems since citywide coverage is neither feasible nor affordable. Contrary to wastewater collection and treatment, faecal sludge management has received little attention until very recently. In many cities, the faecal sludges from on-site disposal systems are dumped untreated, mainly for lack of affordable treatment options.

After having been involved in the development of sustainable pit emptying equipment, SANDEC has embarked on R+D of faecal sludge treatment options. The project "Management of Sludges from On-Site Sanitation Systems" (SOS) aims at developing guidelines for low-cost and moderately sophisticated faecal sludge treatment options. These comprise processes and technologies, that prove sustainable under the varying economic, institutional and technological conditions prevailing in developing and newly industrialising countries. Adequate treatment will allow either an agricultural use of the products from both solids and liquid treatment or their disposal on land or in water with minimal environmental impact.

The design and operational guidelines shall be based mainly on practical field research. Institutions of developing countries interested in working toward the same objective have, therefore, been identified and field collaboration established. A further objective of the SOS Project is to assist the collaborating institutions in strengthening their capacity in faecal sludge and wastewater monitoring, and in conducting applied field research.

Why Collaborative Field Research In Ghana ?

The field research project between the Water Research Institute (WRI) in Accra, Ghana, and SANDEC was the first of currently four collaborative efforts initiated by SANDEC's R+D project on faecal sludge treatment[1]. Ghana is one of the first countries to set up and operate plants for the separate treatment of sludges from septic tanks, bucket latrines and public toilets. Schemes have been in operation in Accra, the country's capital, since the late 1980s. Furthermore, the Water Research Institute, a well-staffed and equipped R+D institution active in the water and waste management field, along with Accra's Waste Management Department, showed great interest in investigating the performance of Accra's two full-scale FS treatment plants of Achimota and

1 Other collaborative projects were initiated to date with AIT in Bangkok, the University of the Philippines in Manila and the University of Rosario in Argentina.

Teshie. Both plants comprise FS pretreatment units for solids-liquid separation in separate sedimentation/thickening tanks, followed by a series of ponds treating the supernatant liquid. In-depth monitoring of these systems was suggested, as it would yield useful information on actual and potential plant performance, relevant operation criteria and process parameters.

SANDEC, therefore, decided to initiate its field research activities in collaboration with WRI in Ghana.

The Series of Discussion Papers

This document is one of a series of discussion papers based on the results of collaborative field research, including reviews of relevant publications. The discussion papers aim at informing professionals working in the waste management field about recent findings on faecal sludge treatment and also at providing preliminary design recommendations. These may have to be adapted in the light of additional knowledge. We hope that the documents will be of use to technical experts planning and designing faecal sludge treatment facilities. Comments are welcome and may be sent to the authors either at WRI or EAWAG/SANDEC. The following discussion papers are now being prepared and will be available shortly:

- *Co-Treatment of Faecal Sludge and Wastewater - A Literature Review*
- *Characteristics and Solids-Liquid Separation of Faecal Sludges*
- *Use of Reed Beds for Sludge Dewatering*

More documents shall be published as the project proceeds, and as more field data and experience are generated which can be put to the use of field practitioners.

1 Introduction

1.1 Why Treat Faecal Sludges ?

Discharge of **untreated** faecal sludges - these are sludges collected from unsewered toilets and from septic tanks - in urban or peri-urban areas results in environmental and public health impacts and is an eyesore to the public. The rationale for treating FS is to reduce or eliminate these risks and impacts. For treatment schemes to actually become implemented, this rationale must be coupled with the political will of the responsible authorities, sound entrepreneurship and a felt need of those directly and indirectly affected by untreated FS disposal.

Below, major potential or actual environmental and health impacts along with a risk characterisation are listed. Differentiation between the different types of impacts is necessary as the type determines possible preventive measures. Potential impacts or risks may also lead to actual impacts. However, it may be difficult to prove the relationship between cause and effect. The transmission of excreted infections is such a phenomenon.

Impact	Type of risk
• Surface and groundwater pollution	Actual surface water pollution; potential for groundwater pollution
• Transmission of excreta-related infections; occurrence of a high level of pathogens in the urban environment	Potential risk of increased levels of disease prevalence; scientific proof of actual risks attributable to the disposal of untreated FS and to high levels of pathogens "floating" within the urban environment may be obtained on the basis of extensive epidemiological studies, only
• Unpleasant odours and eyesore	Impact felt by those dwelling near the disposal sites and by those passing by

1.2 Purpose and Scope of the Document

Purpose

A major aim of this document is to equip the reader with guidance on how faecal sludges collected from on-site sanitation systems may be treated by selected technologies and processes. Emphasis is laid on options which tend to be low in capital and operating costs. In contrast to wastewater treatment technologies, for which a high level of knowledge has been attained also for systems suitable in developing countries, little technical research and development has been conducted on faecal sludge treatment to date. The document will allow the reader to become familiarised with the type of schemes currently operating in Ghana and used to conduct field research. The data presented will provide the reader with the limits and potentials of the respective treatment options, as well as with the gaps-in-knowledge for which answers have not yet been found and which therefore call for further field investigations.

Scope

The treatment of process sludges; i.e., of solids separated from the raw FS through solids-liquid separation processes was not made part of the field investigations. It is therefore discussed in an indicative manner only.

While the document focuses on a limited set of treatment options, i.e. primarily (but not exclusively) those currently being used in Ghana, other options may also well prove feasible. These have not, however, so far been a focus of SANDEC's field research.

1.3 Target Readership

The document was written for urban sanitation planners and engineers having to devise strategic sanitation plans and design faecal sludge treatment schemes in towns and cities using on-site sanitation systems. Also addressed are officials of environmental control agencies, applied researchers and development experts working in the field of urban waste management.

2. Faecal Sludge Quantities and Characteristics

2.1 What is Faecal Sludge ?

Faecal sludges (FS) are sludges of variable consistency accumulating in septic tanks, aqua privies, family pit or bucket latrines and unsewered public toilets. These contents comprise varying concentrations of settleable or settled faecal solids as well as of other, non-faecal matter. Further to this, the sludges exhibit varying degrees of biochemical stability attained through anaerobic digestion mainly, depending on the ambient temperature, retention period, and inhibition or enhancement due the presence of other, non-faecal substances.

Table 1 Human Excreta: Per Capita Quantities and Their Resource Value (Strauss 1985)

	Faeces	Urine	Excreta
Quantity and consistency			
• Gram/cap, day (wet)	250	1,200	1,450
• Gram/cap, day (dry)	50	60	110
• Including 0.35 litres for anal cleansing, gram/cap, day (wet)			1,800
• m^3/cap·year (upon storage and digestion for ≥ 1 year in pits or vaults in hot climate)			0.04-0.07
• Water content [%]			50 - 95
Chemical composition	**% of dry solids**		
• Organic matter	92	75	83
• C	48	13	29
• N	4-7	14-18	9-12
• P_2O_5	4	3.7	3.8
• K_2O	1.6	3.7	2.7

For comparison's sake:	**% of dry solids**		
	N	P_2O_5	K_2O
• Human excreta	9-12	3.8	2.7
• 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

Table 1 contains relevant characteristics and per capita quantities of human excreta, including its resource elements, viz. organic matter, along with phosphorus, nitrogen and potassium as major plant nutrients. Average nutrient contents of plant matter and cattle manure are also included for comparison's sake. Faecal sludges, if adequately stored or treated otherwise, may be used in agriculture as soil conditioner to restore or maintain the humus layer or as fertiliser.

In many places, faecal sludges are traditionally used in agriculture, often untreated or stored for insufficiently long periods, though, to ensure adequate hygienic quality. For a large number of vegetable farmers in China for example, excreta collected in urban areas are still the favoured form of soil conditioner and fertiliser although the sludges may still contain considerable loads of e.g. viable intestinal worm eggs. Many urban consumers in China prefer excreta-fertilised vegetables to crops cultivated with mineral fertilisers.

Table 2 Faecal Sludges from On-Site Sanitation Systems in Tropical Countries: Characteristics, Classification and Comparison with Tropical Sewage (after Strauss et al. 1997 and Mara 1978)

Item	Type "A" (high-strength)	Type "B" (low-strength)	Sewage - for comparison's sake
Example	Public toilet or bucket latrine sludge	Septage	Tropical sewage
Characteri-sation	Highly concentrated, mostly fresh FS; stored for days or weeks only	FS of low concentration; usually stored for several years; more stabilised than Type "A"	
COD mg/l	20, - 50,000	< 15,000	500 - 2,500
COD/BOD	5 : 1 .... 10 : 1		2 : 1
NH_4-N mg/l	2, - 5,000	< 1,000	30 - 70
TS mg/l	• 3.5 %	< 3 %	< 1 %
SS mg/l	• 30,000	≅ 7,000	200 - 700
Helm. eggs, no./l	20, - 60,000	≅ 4,000	300 - 2,000

Table 2 shows typical FS characteristics. It is based on results of FS studies in Accra/Ghana, Manila/Philippines and Bangkok/Thailand. The characteristics of typical municipal wastewater as may be encountered in tropical countries are also included for comparison's sake. Organic strength, ammonium (NH_4-

N) concentrations, solids contents, and helminth egg concentrations of faecal sludges greatly differ from those of municipal wastewater collected in centralised sewerage systems and are normally higher by a factor of 10 or more. The sludges may be classified in two broad categories. Sludges subsequently termed as Type "A", are rather fresh and exhibit high concentrations of organics, ammonium and solids. They originate from non-flush or pour-flush public toilets and bucket latrines. The sludges subsequently termed as Type "B" are of relatively weak strength as the solids separated in the vaults or pits are normally collected along with flush and greywater retained in the tank. Moreover, type B sludges have usually been stored for lengthy periods of time (from one to several years) and, hence, undergone biochemical stabilisation to a considerable extent. Septage normally falls into this category.

The division of faecal sludges into the categories shown in Table 2 is not always possible as FS quality is influenced by a variety of factors (see Fig. 1). It may therefore strongly differ from place to place as is shown in Table 3 which is a comparative listing of septage characteristics in Bangkok, Manila and the U.S.[1]. Bangkok septage appears to be "weak" compared to Manila and U.S. septage, a phenomenon that might be attributable to groundwater intrusion into septic tanks in Bangkok. On the other hand, the fairly high strength of U.S. septage may be caused by the fact that many U.S. households use garbage grinders in their kitchen sinks. The organic fraction (TVS) is amazingly high (≥ 65 %) in all cases although one would excpect that organic matter degradation should be essentially complete, particularly in the warm climates of Bangkok and Manila and given septage storage periods of up to several years.

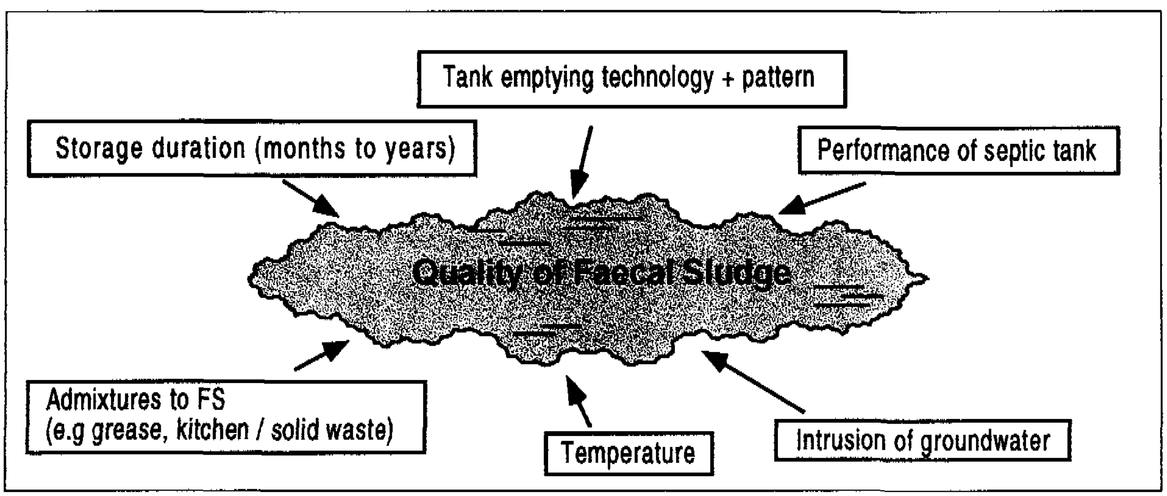


Fig. 1 Factors Influencing Faecal Sludge Quality

1 In the U.S., approximately 25 % of the population are served by septic tanks (U.S. EPA 1984).

Table 3 Septage Quality in Bangkok, Manila and the United States

	COD [g/L]	BOD/ COD	TS [g/L]	TVS [% of TS]
Bangkok [1]	14	-	16	69
Manila [2]	37	1 : 10	72	76
US EPA [3] (mean)	43	1 : 9	39	65

1 Based on AIT (1998)
2 Based on University of the Philippines (1997)
3 Based on U.S. EPA (1984)

When intending to use raw or treated faecal sludge for soil amendment in agriculture or to restore soil fertility in damaged soils, it is important to take heavy metals into account. A restriction in sludge application may become necessary to limit heavy metal accumulation in soils and crops through the repeated application of sludge. There exist, in many countries, regulations regarding the maximum yearly load (kg/ha·year) of specified heavy metals which may be applied to soils, and standards for maximum heavy metal concentrations in sludge applied onto land (Matthews 1996).

Table 4 Heavy Metal Concentrations in Septage and EU Standard for Admissible Levels in Sludges Used in Agriculture

	Heavy metal concentrations in septage, g/kg TS			
	Bangkok (15 samples)	**Manila** (12 samples)	**U. S.** average	EU tolerance values for sludge
Cd	2.8	5.3	18	20 - 40
Pb	6.8	84	216	750 - 1,200
Cu	289	64	165	1,000 - 1,750
Zn	2,085	1,937	1,263	2,500 - 4,000
Cr	20	16	28	1,000 - 1,500

Table 4 shows heavy metal (HM) concentrations in faecal sludges collected in Bangkok and Manila. FS are usually "cleaner" than sewage treatment plant sludges, as they tend to contain less heavy metals or refractory organics. Exceptions may be found in places where septage is also collected from septic tanks serving cottage or small industrial enterprises. Also listed in Table 4 are the tolerance values for HM concentrations in sewage sludge used in agriculture as stipulated by the European Union. These reflect the fact that sewage sludge often carries considerable loads of heavy metals originating from industrial wastewater discharges. In a number of countries, sludge tolerance values are considerably lower than stipulated by the EU. In Switzerland, e.g., the limits are set at least 50 % lower.

2.2 Per Capita Quantities of Faecal Sludge

Table 5 contains the daily per capita volumes and constituent contributions in faecal sludges collected from septic tanks, pit and bucket latrines, as well as from low or zero-flush, unsewered public toilets. Values for fresh excreta are given as reference. The figures are overall averages and may be used for planning and preliminary design. Actual quantities may, however, vary from place to place. The daily per capita BOD for septage appears to be very low when compared with the figures for fresh excreta. The phenomenon can be explained with the fact that more than 50 % of the BOD load entering the septic tank is removed by anaerobic digestion during the storage of the faecal sludge. A further portion of the BOD is "lost" through the discharge of the supernatant into soil infiltration systems or into surface drains.

The reliability of the sludge collection has certainly also an effect of the amount of BOD which finally arrives with the septage on the treatment plant.

Table 5 Daily Per Capita Volumes; BOD, TS, and TKN Quantities of Different Types of Faecal Sludges

Variable	Septage [1]	Public toilet and bucket latrine sludge [1]	Pit latrine sludge [2]	Fresh excreta
• BOD g/cap·day	1	16	8	45
• TS g/cap·day	14	100	90	110
• TKN g/cap·day	0.8	8	5	10
• l/cap·day	1	2 (includes water for toilet cleansing)	0.15 - 0-20	1.5 (faeces and urine)

1 Estimates are based on a faecal sludge collection survey conducted in Accra, Ghana.

2 Figures have been estimated on an assumed decomposition process occurring in pit latrines. According to the frequently observed practice, only the top portions of pit latrines (~ 0.7 ... 1 m) are presumed to be removed by the suction tankers since the lower portions have often solidified to an extent which does not allow vacuum emptying. Hence, both per capita volumes and characteristics will range higher than in the material which has undergone more extensive decomposition.

3. Treatment Goals and Options

3.1 Effluent and Plant Sludge Quality Guidelines

What effluent and plant sludge quality criteria should one meet when planning and designing a faecal sludge treatment plant (FSTP) ?

In many of the less industrialised countries, effluent and natural water quality standards do not exist. In others, effluent discharge standards may exist for wastewater but not for faecal sludges. Faecal sludge treatment standards have been established in China and Ghana. In China, faecal sludge treatment requires a ≥ 95 % helminth egg removal or inactivation (National Nightsoil Treatment Standards, P.R. China 1987). In Ghana, the Environmental Protection Agency has stipulated a 90 % BOD and faecal coliform removal for the effluent to be discharged from the New Teshie FSTP in Accra (Annoh 1995). General effluent standards are currently being drafted. The Indonesian government has issued design guidelines for septage treatment in 1992 (Ministry of Public Works, Indonesia 1992). However, effluent and plant sludge quality standards or guidelines are not stipulated in the respective document. In the Province of Santa Fé, Argentina, e.g., wastewater FS treatment plant effluent standards for BOD, COD, SS and fecal coliforms (FC) are set at 50, 125, 60 mg/l, and 10^5/100 ml, respectively. For effluents from waste stabilisation pond systems, BOD and COD values apply to filtered samples. Sludges used in agriculture may not contain more than 1 helminth egg per 4 g TS (Ingallinella 1998). The European Union, in setting standards for the agricultural use of sludges from sewage treatment plants and septic tanks, stipulates that all sludges must be treated prior to use unless they are worked into the soil and minimum waiting periods are observed after application of the sludge. Use of the sludge shall take into account the nutrient needs of the plants, and may not impair ground or surface waters. Specific standards have been stipulated regarding heavy metal concentrations in sludge and cumulative loads applied to the soils (Council of The European Communities 1986).

The following should be taken into consideration when establishing FSTP effluent and plant sludge quality guidelines:

- **"Some may sometimes mean a lot"**: Currently, faecal sludges are generally dumped uncontrolled and untreated into the aquatic and terrestrial environment. Treating the sludges prior to discharge or use will, in itself, constitute substantial health and environmental improvements even if stringent quality standards are not met.

- **Highly concentrated waste**: faecal sludges are 10-100 times more concentrated than municipal wastewater. Reaching of effluent quality levels similar to those of wastewater treatment plant effluents is therefore particularly challenging.

- **Economically beyond reach**: to set unduly strict quality levels may, in most cases, be unfeasible for economic reasons. To meet stringent standards, land requirements would be excessive if low-cost treatment technologies were used. Alternatively, if more sophisticated options were selected, capital and operating costs would become unaffordable.

- **Widely varying parameters**: the raw sludge quality differs greatly, particularly between relatively weak faecal sludges, such as septage, and fresh, more concentrated sludges, such as the contents from unsewered, non-flush or low-flush public toilets. To attain uniform quality standards may thus be rather difficult.

Faecal Sludge Dumping into the Sea.

"Some may sometimes mean a lot." Treating the sludges prior to discharge or use will, in itself, constitute substantial health and environmental improvements even if stringent quality standards may not be met.

- **Discharge vs. reuse**: when establishing effluent and plant sludge quality standards, a distinction should be made between the discharge of faecal sludge or its treated forms into the aquatic or terrestrial environment and their use in agriculture or aquaculture, respectively.

For the FS discharge into the environment, parameters such as COD or BOD and NH_4 are of prime importance. When discharging them into aquatic environments, such as seasonal or perennial rivers, estuaries or the sea, their degree of dilution in the receiving water body should be taken into consideration. However, from an ecological viewpoint, thresholds should be established in terms of discharged pollutant loads (expressed, e.g. as tons of COD/year) rather than in terms of pollutant concentrations.

If the treated FS is to be reused, the important variables are hygienic characteristics such as helminth eggs as parasite indicators, and faecal coliforms as bacterial indicators.

- **Institutional capacity and political will:** when establishing quality guidelines, the institutional capacities for controlling and enforcing them should also be taken into account. Typically, less industrialised countries lack trained personnel and laboratory facilities to carry out routine monitoring. Moreover, political will and legal tools may be inadequate to enforce quality standards. Violation of effluent standards may, therefore, go undetected. Monitoring requirements can be minimised if use is made of treatment options which, if properly designed, constructed and operated below or at design loads, are known to meet given effluent standards. WSP are, for example, a treatment option not requiring frequent monitoring.

Table 6 lists recommendations for FSTP effluent standards. They are based on the still limited field data on FSTP treatment performance. For the use of FS in agriculture, the nitrogen requirements of the crops to be fertilised constitute a critical limiting factor. These range from 100 to 200 kg N/ha·year, depending on the type of crop. Excess loading is likely to lead to impaired growth and to groundwater pollution.

The suggested guidelines are tentative figures requiring careful examination in the light of specific local situations. Economic aspects and the specific FS characteristics have been taken into consideration. The guidelines may appear less stringent compared to commonly used wastewater effluent quality guidelines. Yet, care should be taken when trying to enact more stringent quality guidelines as they would lead to major additional investments and call for more sophisticated technologies which would, in turn, render plant maintenance and operation more difficult and costly.

Table 6 Suggested Effluent and Plant Sludge Quality Guidelines for the Treatment of Faecal Sludges

	COD [mg/l]	BOD [mg/l]	NH_4-N [mg/l]	Helm. eggs [No./l]	Faecal colif. [No./100 ml]
A: Liquid effluent					
Treatment for discharge into receiving waters:					
• Seasonal stream or estuary					
- unfiltered	≤ 300-600	≤ 100-200	≤ 10-30	≤ 2-5	$\leq 10^4$
- filtered	100-150	30-50			
• Perennial river or sea					
- unfiltered	≤ 600-1,200	≤ 200-500	≤ 20-50	≤ 10	$\leq 10^5$
- filtered	150-250	50-70			
Treatment for reuse:					
• Restricted irrigation	n.c.	n.c.	*	≤ 1 **	$\leq 10^5$ **
• Vegetable irrigation	n.c.	n.c.		≤ 1 **	$\leq 10^3$ **
B: Treated plant sludge					
• Use in agriculture	n.c.	n.c.	n.c.	≤ 3-8/g TS ***	Safe level if egg standard is met

n.c. - not critical

* Irrigation rates and effluent quality must be chosen such that the crop's nitrogen requirements (100 .... 200 kg N/ha·year, depending on the crop) are not exceeded.

** WHO (1989)

*** Based on the nematode egg load per unit surface area derived from the WHO guideline for wastewater irrigation (WHO 1989), and on a manuring rate of 2-3 tons of dry matter/ha·year (Xanthoulis and Strauss 1991)

3.2 Overview of Treatment Options

Fig. 2 shows theoretical faecal sludge treatment options likely to be appropriate for developing and newly industrialised countries (Strauss and Heinss 1995). When classifying faecal sludge treatment options, one basic distinction is made between **options with** and **without solids-liquid separation**. Another way of classifying FS treatment options is to distinguish between separate treatment of faecal sludges and co-treatment. Co-treatment comprises options treating septage or latrine sludges together with municipal wastewater, wastewater treatment plant sludge, household/municipal solid waste, and with organic residues (e.g. sawdust or woodchips).

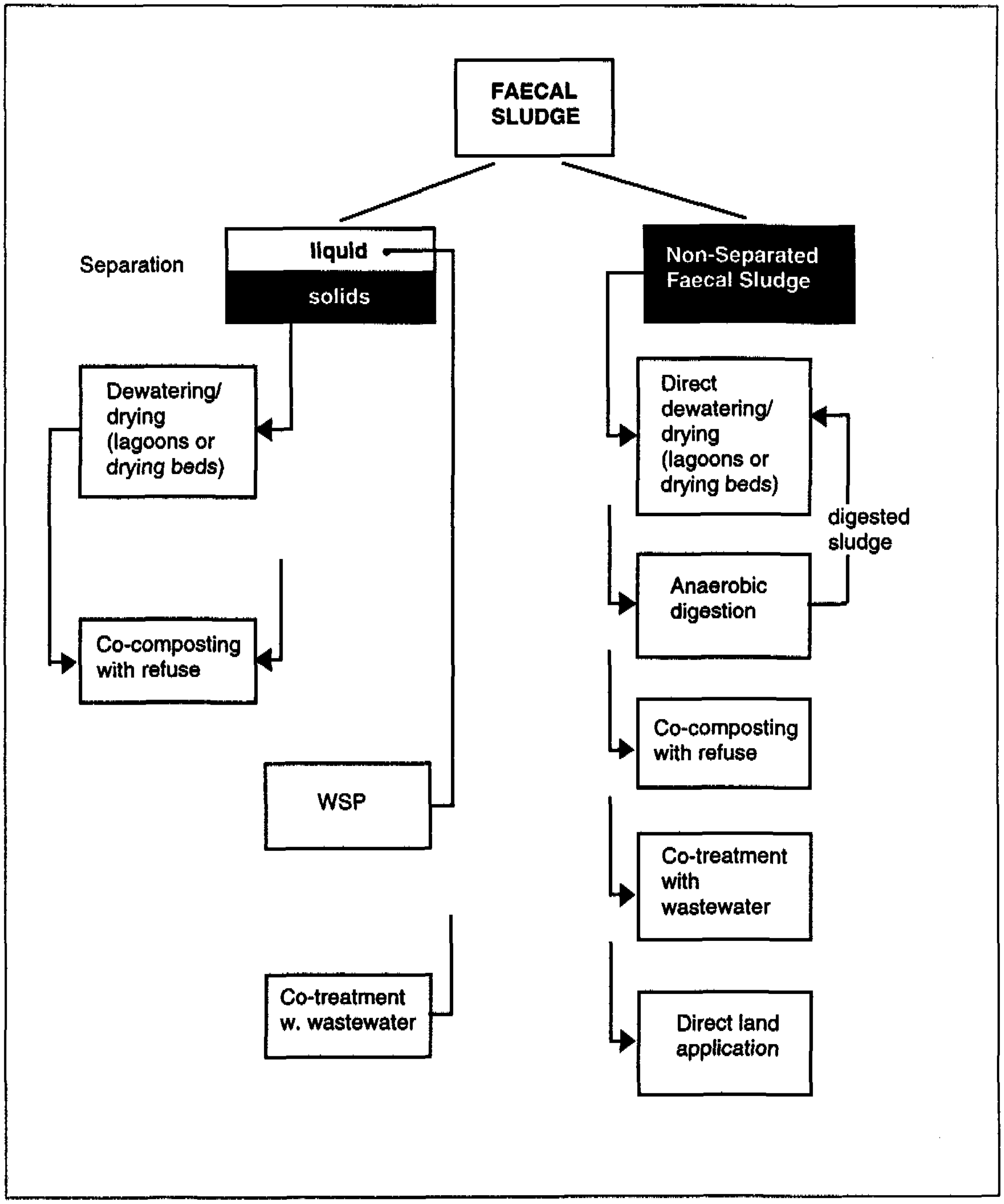


Fig. 2 Theoretical Options for Treating Faecal Sludges

Priority Options

Methods for treating human waste in developing and in newly industrialised countries should, in most cases, be of relatively low-cost; i.e., low in capital and operating costs. Chosen systems must also be compatible with the expertise available in the particular country at various professional levels, and with the institutional/entrepreneurial set-up responsible for scheme implementation and servicing. The preferred options will, in most cases, comprise low or modest levels of mechanisation and concomitant minimum external energy input. The disadvantage of treatment options of low capital and operating costs is their large land requirements. This, in turn, creates a great challenge to the fast growing urban agglomerations where land becomes increasingly scarce and, hence, relatively costly. Therefore, when selecting appropriate options for the treatment of faecal sludges (and wastewater), a judicious choice must be made with respect to these factors - economic and technical feasibility vs. land requirement. A feasible strategy may consist in establishing an optimum number of decentralised, small to medium-sized treatment plants serving a selected number of urban districts or zones. Haulage distances for vacuum tankers will thereby also be reduced.

3.3 Treatment Options Dealt with in this Document

At the onset of SANDEC's collaborative field research programme on faecal sludge treatment, the treatment facilities then already operating in Accra, Ghana, and the expertise available at Ghana's Water Research Institute, provided a suitable base to initiate field research. The fact that stabilisation ponds offer a potentially viable solution for faecal sludge treatment in the tropics led us to embark on investigating this type of treatment as the first collaborative field research activity. This document is based on the results obtained during the investigations on solids-liquid separation and on pond treatment conducted in Accra. Information and conclusions drawn from relevant literature on faecal sludge or wastewater treatment are also included.

Fig. 3 contains a schematic diagram of the Achimota FSTP in Accra/Ghana. The treatment system developed by Annoh and Neff (1988) includes a solids-liquid separation step in settling/thickening tanks, followed by a series of four anaerobic ponds, a trickling stack, a "maturation" pond and a series of evaporation beds. The solids separated off in the settling tanks are co-composted with sawdust, an abundant and appropriate by-product of the local timber industry. In other places where sawdust is not available, the co-composting with refuse may be more appropriate. The Achimota FSTP was used to conduct field studies to assess operation and performance of the **sedimentation/thickening tanks,** including the series of four **ponds** treating the supernatant from the solids-liquid separation step (ponds Nos. 1-4 in the figure) (Larmie 1994 a and b; Larmie 1995; Larmie 1997).

Little has been published to date on faecal sludge treatment in ponds, since ponds exclusively treating faecal sludge have not been widely applied. A few faecal sludge ponds are in operation in Ghana and Indonesia. In contrast, wastewater treatment in waste stabilisation pond (WSP) systems has progressed significantly in recent years and the respective design principles are now well established. While certain processes and design principles of WSP are also applicable to faecal sludge ponds, appropriate pond treatment for faecal sludge requires the development of specific design and operational guidelines. Simply using WSP design criteria for FS ponds will lead to uneconomical designs and inadequate plant performance.

A separate study was conducted to assess the sludge accumulation pattern in the settling/thickening tanks of the Achimota FSTP. Its objective was to understand the tanks' loading limits and to define sludge storage as an assumed design criterion for faecal sludge sedimentation tanks.

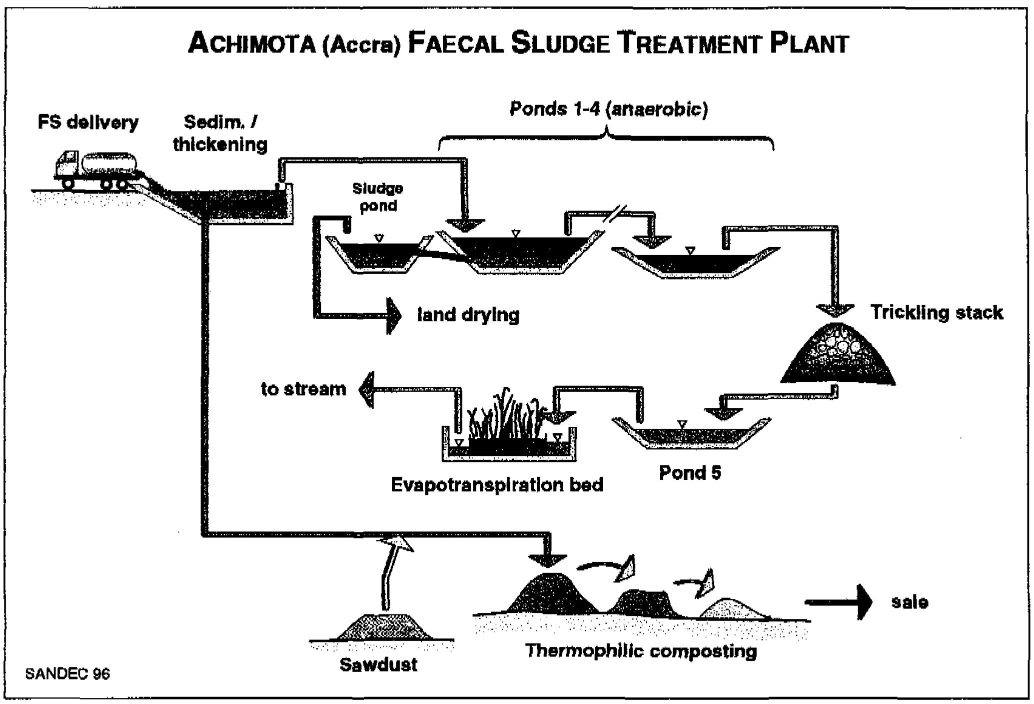


Fig. 3 Schematic Diagram of the Achimota FSTP in Accra, Ghana

Field research in Accra also comprised sludge dewatering/drying tests with a series of unplanted pilot-scale **sludge drying beds** of 3.5x3.5 m each installed on the premises of the Ghana Water Research Institute. Results thereof are summarised in this report. Land requirements of drying beds and settling/thickening tanks are calculated and compared, and the selection criteria for the two processes are listed.

The sludge produced in the first of a series of five ponds treating the supernatant from the settling/thickening tanks, flows into an adjacent sludge pond through a bottom pipe connecting the two ponds. It is then pumped from the sludge pond by suction tankers and allowed to dry naturally on the plant's premises. The investigations did not cover this drying process, or the co-composting with sawdust of the settling tank solids.

4. Solids-Liquid Separation

4.1 Why Should Solids be Separated Prior to Pond Treatment ?

Apart from screening and grit removal units, wastewater stabilisation ponds are normally not equipped with mechanical solids-liquid separation facilities. Settling processes occur mainly in the primary anaerobic pond. However, pond systems designed to treat faecal sludge have to meet special requirements as the solids concentration in faecal sludge is significantly higher than in wastewater. As stated in Chpt. 2.1, the suspended solids concentration in faecal sludge is 10 to more than 100 times higher than in municipal wastewater. Thus, the problem of high solid loads should be taken into consideration when planning pond systems for faecal sludge treatment. A well functioning FS pond system is mainly dependent on a reliable solids separation. Solids build-up in primary ponds caused by too infrequent emptying and inadequate pond design has, in fact, been reported by Hasler (1995) and Mara et al. (1992), and has led to a malfunctioning of the entire pond system.

Treatment options for solids-liquid separation such as gravity sludge thickeners, centrifuges, filtration (vacuum or pressure) or other methods comprising electrically driven mechanical equipment are not discussed in this document. In most places where a pond system is chosen as the preferred option for treating faecal sludges, the aforementioned separation methods are likely to be too expensive and sophisticated to be sustainably operated and maintained. Irregular power supply, poor daily maintenance and lack of spare parts are likely to render these installations inoperative within a few months after commissioning.

Scum Covered Settling Tank (foreground) and Anaerobic Ponds (background)

A well functioning FS pond system is dependent on a reliable solids separation. (Achimota FSTP, Accra, Ghana)

Sedimentation/thickening tanks such as the ones, which have been operating in an FSTP in Accra/Ghana for the past eight years, offer a suitable option for solids-liquid separation. Sludge drying beds, which have been field tested in Ghana on a pilot scale, may constitute another low-cost technology enabling solids-liquid separation. Use of primary ponds is a third option briefly discussed. Open problems and questions are described in Chpt. 9, "Needs for Further Field Research".

4.2 Sedimentation/Thickening Tanks

The twin sedimentation tanks developed in Ghana by Annoh and Neff (1988) for the Achimota and other FSTPs in Accra and Koforidua are batch-operated and loaded by vacuum trucks at the shallow end. Loading near the deep end of the tank would probably improve solids separation (see Chpt. 8.3.1. on improved design). At an average daily loading of 150 m^3/d, the tank will be filled within two days and work from then on as sludge accumulator similarly to a septage tank. The settled sludge is stored and the supernatant flows from the tank into the following pond. An operating cycle lasts from four to eight weeks. Sludge loading is then transferred to a parallel tank. The settled and thickened sludge is removed at the latest point in time when the tank is due for a new operating cycle.

Removal of Separated Solids from a Settling Tank

The tanks which are accessed via a ramp are emptied by front-end loaders. (Achimota FSTP, Accra, Ghana)

Consolidation periods thus last from one to four months depending on whether the plant comprises two or three parallel tanks. The tanks, which are accessed by a ramp, are emptied by front-end-loaders. Fig. 4 illustrates schematically the type of tank currently in use at three FSTP sites.

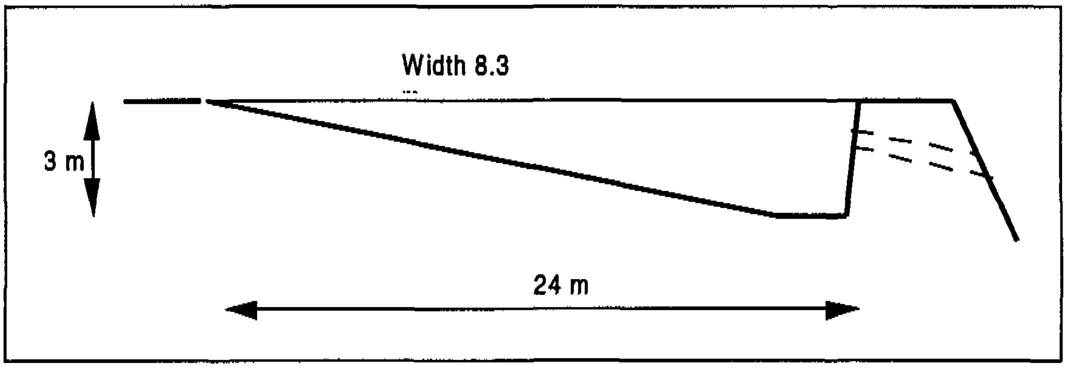


Fig. 4 Schematic Illustration of a Batch-Operated, Rectangular Sedimentation/Thickening Tank with a Ramp for Solids Removal by Front-End Loader (based on the design by Annoh and Neff 1988)

Although the tank's organic loading rate is not used as design parameter, calculations have revealed that it ranges as high as 1,000 - 1,500 g BOD/m^3·d. This loading rate exceeds three to five times the standard value for anaerobic ponds and may, therefore, cause odour problems. However, according to the authors' own observations, the area around the tank is basically odour-free due mainly to the forming of a stable scum layer on the sedimentation tank a few days after commissioning.

Fig. 5 shows cumulative solids loading and suspended solids (SS) removal plotted as a function of tank operating time as observed at the Achimota FSTP. The tank's geometry, hydraulic design and mode of operation influence elimination rates in the tank. The following average removal rates (average based on hourly and two daily samples) were reached in the sedimentation tank effluent during the period of investigation from July-Oct. 1994 (expressed in % of the raw sludge concentrations):

- BOD and COD: 30 – 50 %
- SS: 60 %
- Helminth eggs: 50 %

During the first five days of tank operation, significant BOD and SS removal amounting to 55 % and 80 %, respectively, was attained in the supernatant. Solids removal (SS) remained above 40 % for a period of three weeks, however, BOD removal rapidly dropped below 20 % after about ten days. Prolonged high removal could be achieved by optimising the tank geometry and limiting the loading periods to ≤ 15-20 days (see also Chpt. 8.3.1).

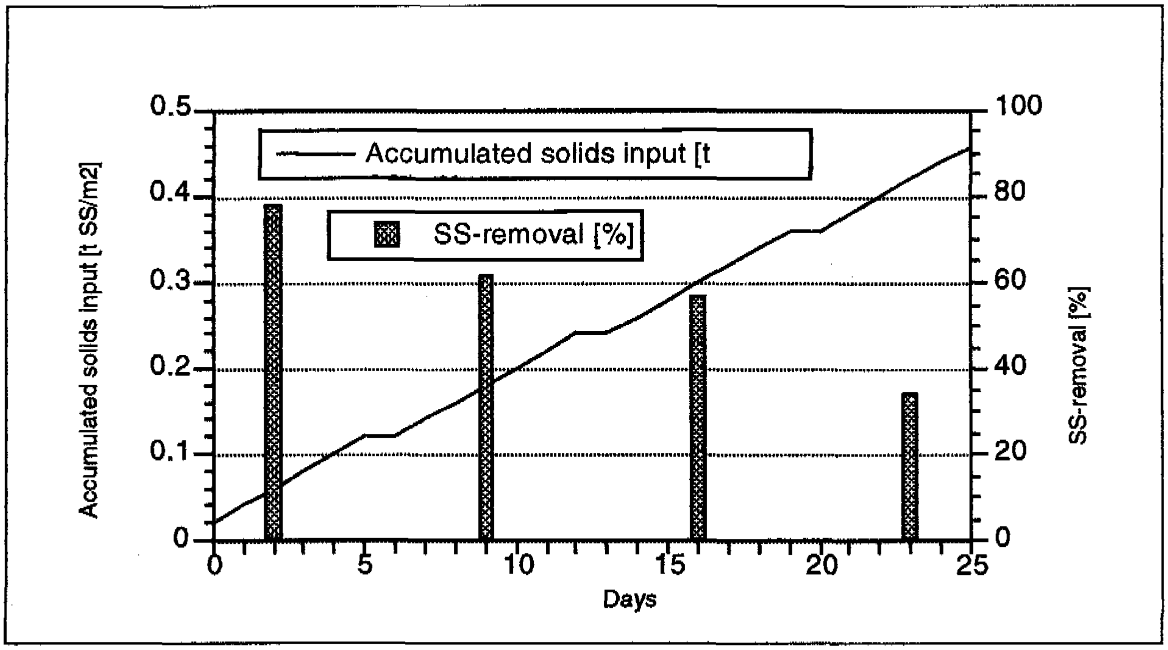


Fig. 5 Solids Loading and Removal Efficiency in the Sedimentation/Thickening Tank of the Achimota FSTP (Accra, Ghana) as a Function of Operating Time

The settled sludge in the sedimentation tank of the Achimota FSTP (Accra) reaches a TS content of up to 15 % (150 g/l) even without optimal hydraulic design and loading pattern. This is the maximum attainable TS value when easily dewaterable sludge is thickened without chemical conditioning. The TS concentration in the scum layer was higher than that in the settled sludge (up to 180 g/l), presumably due to flotation and continuous sun drying. SS concentrations of 4 g/l were measured in the clear water zone.

The retention period for the separated sludge solids ranges in the order of ≥ 4 weeks (equivalent to the tank's consolidation period). Given the fairly long storage, it is expected that the settled sludge will be stabilised by anaerobic digestion. Results from settled sludge analyses revealed that the share of volatile suspended solids (VSS) was in fact reduced by 10 % (from 70 to 60 %) during the four weeks of consolidation.

4.3 Unplanted and Planted Sludge Drying Beds

Sludge drying beds, if suitably designed and operated, can produce a solids product, which may be used either as soil conditioner or fertiliser in agriculture, or deposited in designated areas without causing damage to the environment. In most cities, the solids removed from the drying beds after a determined period (several weeks to a few months) require further storage and sun drying to attain the hygienic quality for unrestricted use. Where dried sludge is used in agriculture, helminth (nematode) egg counts should be the decisive quality criterion in areas where helminthic infections are endemic. A maximum nematode (roundworm) egg count of 3-8 eggs/g TS has been suggested by Xanthoulis and Strauss (1991) (see also Chpt. 3.1 for a discussion and listing of quality guidelines).

Although drying bed treatment is usually not classified as a solids-liquid separation process, it serves to effectively separate solids from liquids and to yield a solids concentrate. Gravity **percolation** and **evaporation** are the two processes responsible for sludge dewatering and drying. In planted beds, **evapotranspiration** provides an additional effect. Unplanted and planted sludge drying beds are schematically illustrated in Fig. 6. A frequently observed phenomenon is the fact that when fresh, anaerobic sludges are loaded onto the drying beds, the sludge solids rise to the surface due to degasification. This enhances the solids-liquid separation process and reduces resistance to seepage. Evaporation causes the mud to crack, thereby leading to improved evaporative water losses and enhanced drainage of the sludge liquid and rainwater.

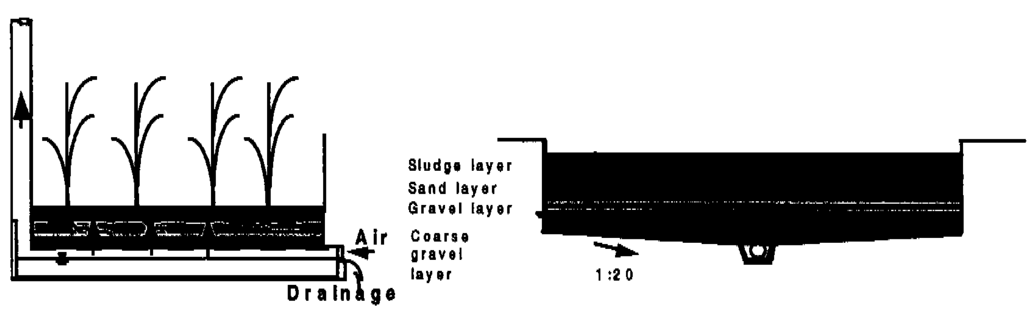


Fig. 6 Planted and Unplanted Sludge Drying Beds (schematic)

From 50 - 80 % of the faecal sludge volume applied to unplanted drying beds will emerge as **drained liquid** (percolate). The ratio between drained and evaporated liquid is dependent on type of sludge, weather conditions and operating characteristics of the particular drying bed. In planted drying beds, this ratio is likely to be much lower. Drying bed percolate tends to exhibit considerably lower levels of contaminants than settling tank supernatant. This liquid will, nevertheless, also have to be subjected to a suitable form of treatment (e.g. in facultative ponds).

Pescod (1971) conducted experiments with **unplanted** sludge drying beds in Bangkok, Thailand. Twelve experiments with faecal sludges of variable solids content (TS = 1.7 % - 6.5 %) and different dosing depths were conducted during the rainy and dry season. According to the experiments, maximum allowable solids loading rates can be achieved with a sludge application depth of 20 cm. To attain a 25 % solids content, drying periods of 5 to 15 days are required depending on the different bed loading rates applied (70 - 475 kg $TS/m^2 \cdot yr$).

Results from pilot sludge drying beds obtained by the Ghana Water Research Institute in Accra/Ghana indicate their suitability for public toilet sludge, septage/public toilet sludge mixtures and primary pond sludge (TS = 1.6 - 7 %). Experiments were conducted during the dry season with sludge application depths of ≤ 20 cm. Average temperature and period of sunshine, including pan evaporation, amounted to 27 °C, 7.8 hours/day and 5.4 mm/day, respectively. TS concentrations after a period of eight days as a function of TS loading rate are given in Fig. 7. The scattering of the plotted points reveals that the dewatering characteristics of the analysed faecal sludges varied significantly.

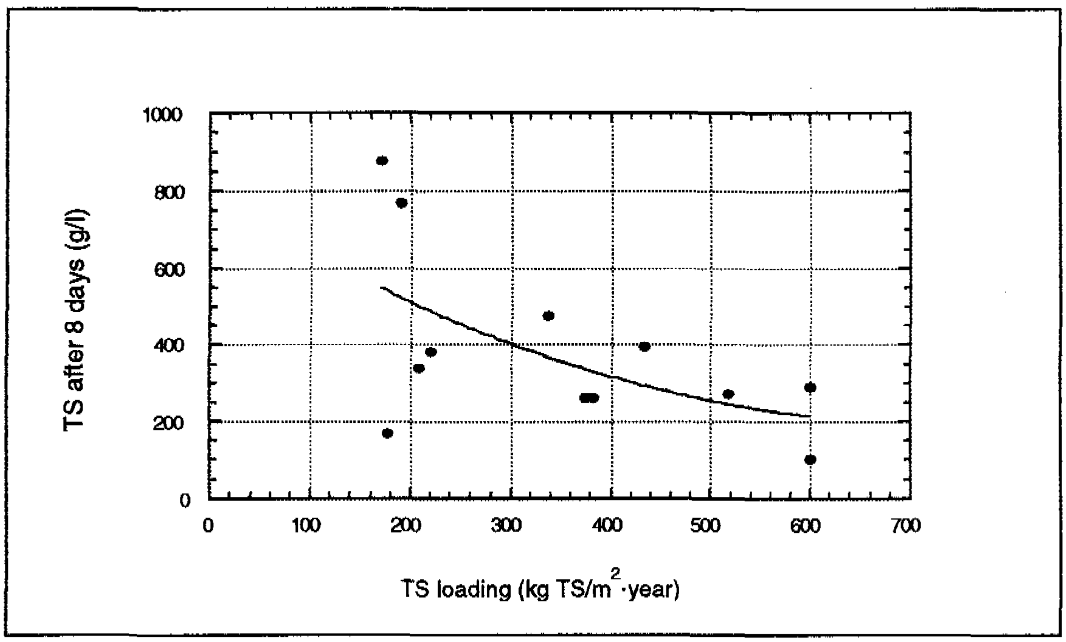


Fig. 7 TS Content vs. TS Loading Rate of Faecal Sludges Treated on Sludge Drying Beds

The various types of sludges revealed the following drying behaviour over a period of eight days:

- Mixtures of public toilet sludge (Type A) and septage (Type B) at a 1:4 ratio:

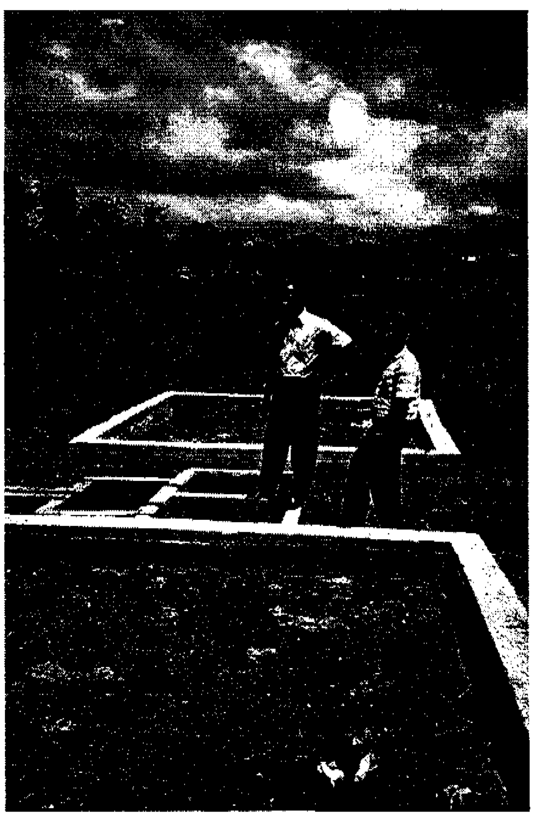
  Good dewaterability, drying to max. 70 % TS in eight days

- Primary pond sludge:

  Rather good dewaterability, drying to 40 % TS

- Public toilet sludge (Type A):

  Erratic results, from almost no dewaterability to 29 % TS. This variability can very likely be attributed to differences in age of the collected sludge, which, in turn, is dependent on emptying frequency of the public toilets. Digested sludge dewaters more easily than undigested sludge. Fresh, nearly undigested sludge therefore hardly lends itself to dewatering on drying beds.



Pilot Sludge Drying Beds

Results from pilot sludge drying beds obtained by the Ghana Water Research Institute in **Accra/Ghana** show a good applicability of sludge drying beds for septage/public toilet sludge mixtures and for primary pond sludge

Sludge dewatered to ≤ 40 % TS in the Accra/Ghana experiments, still exhibited considerable **helminth egg** concentrations. This is not surprising as the drying periods amounted to 12 days at the most. In the few experiments where ≥ 70 % TS contents were attained, no helminth eggs were recovered. The database is, however, yet too scarce to ensure complete egg elimination at this level of dryness. Based on current knowledge of *Ascaris* egg survival, several months of storage at temperatures of ≥ 25 °C or sludge water contents of ≤ 5 % (TS ≥ 95 %) (Feachem et al. 1983) must be attained to ensure complete egg inactivation. High ambient temperatures will yield high levels of dryness fairly rapidly. In such a situation, a few weeks of storage in layers ≤ 20-30 cm on drying beds or on open ground may suffice to attain the desired level of residual egg concentration. To guarantee a hygienically safe product for use in agriculture, further controlled sludge drying experiments should be conducted to determine safe drying periods and required sludge dryness.

When the contaminant levels in the drained liquid of the pilot beds in Accra were compared with the levels in the raw sludges applied, the following average removal rates were calculated from 12 bed loadings:

- Susp. solids: ≥ 95 %
- COD: 70-90 %
- Helminth eggs: 100 %
- NH_4: 40-60 %

Removal of the dewatered or dried sludge is very labour-intensive or requires mechanical equipment. This is a disadvantage associated with unplanted sludge drying beds. **Planted sludge drying beds**, often designated as reed beds, could minimise the need for frequent removal of dried sludge as these can be operated for several years before sludge removal becomes necessary. A number of reed beds treating sewage sludge have been operating successfully in Europe and in North America over periods of up to eight years without sludge removal (Liénard et al. 1990; Kim and Smith 1995). Although their suitability for faecal sludge treatment remains to be tested, this technology is assumed to be a feasible treatment option. Previous experiences reveal that good permeability is maintained despite an increasing sludge height on the bed. This may be attributed to the permanent root growth, which prevents clogging of the soil/sludge filter. Experiments showed that the growth of reeds could be hindered or even fully suppressed if strongly anaerobic sludges are applied (Liénard et al. 1990). Reed beds treating faecal sludges, therefore, require a passive ventilation system to avoid anaerobic conditions in the root zone.

Experience with planted and unplanted drying bed treatment of activated sludge indicates that considerable reductions of ammonia (NH_4 + NH_3) are achieved during the passage of the liquid through the bed (Liénard et al. 1994;

Heinss et al. 1997a). Ammonium nitrogen (NH_4-N) reductions are particularly high in planted beds. As a consequence, ammonia (NH_3) toxicity for algae is unlikely to occur if drying bed percolate is treated in facultative ponds, as reduced NH_4 levels automatically lead to lower NH_3 concentrations. In the first drying bed experiments conducted with faecal sludges in Accra, Ghana (Larmie 1995 and 1996), NH_4 reductions of 50 % were attained. NH_4 + NH_3 removals in the percolate of the planted sludge drying beds operated at AIT in Bangkok, ranged from 70 - 90 % during the first 10 months of operation (AIT 1998). In these beds, which are equipped with a natural venting system, nitrification plays a crucial role.

Planted Pilot Drying Beds at AIT, Bangkok

Planted sludge drying beds, also designated as reed beds or constructed wetlands, could minimise the need for frequent removal of dried sludge as they can be operated for several years before sludge removal becomes necessary.

4.4 Sedimentation/Thickening Tanks vs. Primary Ponds

Similar to wastewater stabilisation ponds, separation and partial stabilisation of the solids in a deeper anaerobic primary pond is also possible for FS pond systems. However, the size of the solids storage volume must be much larger or the pond sludge removed more frequently compared to anaerobic ponds treating wastewater. Assuming for example a TS removal of 80% in the primary pond, a TS content of 3.0 % in the faecal sludge influent mixture (see also Table 2, Chpt. 2.1) and a resulting 18 % TS content in the settled and thickened sludge, a solids storage volume of 0.13 m^3 per m^3 (13 %) of raw FS discharged to the pond will be required.

The question whether it is more practical to use a sedimentation/thickening tank for solids separation and, thereby, limit the desludging periods to a few weeks, or to desludge a pond every 0.5-2 years when the first pond is used for solids separation, can only be answered in the local context. Desludging of a primary pond may be associated with technical and logistic difficulties; i.e., the settled solids may not be pumpable, as they will have become too dense during the extensive storage period. The time required for the settled solids to become spadable; i.e., drying of settled sludge thicker than 30 cm to reach a TS content of ≥ 20 % is extremely long as the water only evaporates very slowly from below the top layer. Moreover, the large volume of separated solids to be removed from primary ponds may require excessive space for further storage and drying. However, organisation of regular, monthly desludging operation of a sedimentation-thickening tank may also be difficult.

Table 7 lists the perceived advantages and disadvantages of both methods.

Table 7 Comparison of Sedimentation/Thickening Tanks vs. Primary Ponds for Solids-Liquid Separation Ahead of a Pond System

	Primary pond as sedimentation unit	**Sedimentation/ thickening tank**
Construction	Very simple; only limited additional costs	More costly but simple in construction
Daily operation	No mechanical equipment required	No mechanical equipment required
Sludge removal	Every 0.5-2 years; very large sludge volumes	Every few weeks; small sludge volumes
Experience	?	Two treatment plants in operation in Accra using sed./thickening tanks; tanks are fairly regularly desludged; occasional overloading due to delays in emptying
Possible problems	Handling of huge sludge volumes; area for subsequent treatment must be larger (e.g. composting, storage, drying); since operation / maintenance is very irregular it tends to be neglected	Organisation of regular desludging operation demands a reliable institutional management structure at municipal level to support adequate operation and maintenance.

4.5 Land Requirement for Sedimentation/Thickening Tanks and Sludge Drying Beds

Approximate land requirements for settling/thickening tanks and for unplanted sludge drying beds can be estimated, based on the monitoring results obtained in Accra/Ghana (see Chpts. 4.2 and 4.3 above). Table 8 provides an estimate of plant size in terms of square meters required per capita.

Table 8 Land Requirements for Settling/Thickening Tanks and Drying Beds

	Attainable TS %	Assumed Loading cycle	TS loading kg TS/m^2·yr	Required area m^2/cap[1)]
Sedimentation/ Thickening Tank	• 14	8-week cycle (4 weeks loading + 4 weeks consolidating; 6 cycles annually); two parallel settling tanks	1,200	• <u>0.006</u>
Sludge Drying Bed (unplanted)	• 70	10-day cycle (loading-drying-removing; 36 cycles annually)	100 - 200	<u>0.05</u>

1) Assumed parameters: FS quantity = 1 litre/cap·day; TS of the untreated FS = 20 g/l

The dewaterability and thickenability of the faecal sludges are important factors determining area requirements.

Sedimentation/thickening tanks require a much smaller per-capita area than sludge drying beds, as the process of separating settable solids requires relatively short hydraulic retention. The space required to store the separated solids bears little on the area requirement. In contrast to this, dewatering and drying of thin layers of sludge on sludge drying beds calls for comparatively long retention periods. Organic and solids loads in the percolate of drying beds are significantly lower than in the effluent of sedimentation/thickening tanks. Hence, less extensive treatment is necessary. Percolate (underdrain) flows from drying beds will amount to 50-80 % of the raw FS deliveries only, whereas the supernatant flows from settling/thickening tanks amount to 95 %, approximately, of the raw sludge discharged into the tanks.

4.6 Solids Treatment

The thickened, dewatered or partially dried sludge ("process sludge"), obtained after solids separation by sedimentation or on sludge drying beds, requires further treatment. The treatment objectives are dependent on the final use of the process sludge, viz. in horticulture, agriculture or landfilling. Respective quality criteria are discussed and listed in Table 6 (Chpt. 3.1). Dewatering or partial sun drying of the solids from sedimentation or primary pond units will be required where the process sludge is to be transported as a spadable product. This will also significantly reduce transport volumes (sludge volumes are halved if the water content is reduced for example from 90 to 80 %).

SANDEC's field research did not focus on the treatment of solids removed from the stream of faecal sludges. We, therefore, restricted ourselves to suggesting the following options:

- For process sludges produced by sedimentation scum formation in settling/thickening tanks or in primary ponds:
    - Dewatering/drying on sludge drying beds
    - Dewatering/sun-drying on open land within the FSTP premises
    - Co-composting with for example municipal/organic refuse or with an alternate organic material such as sawdust or woodchips

  Note: The dewatering/drying period is dependent on climatic conditions and may range from days to weeks to obtain a spadable product for landfilling; or to several months if the solids are to be used in agriculture.

- For pre-dried sludges from sludge drying beds destined for agricultural use (assuming that for economic reasons the bed system is not designed to allow drying to a hygienically safe level):
    - Further sun drying on open land within the FSTP premises (no further drying is required if the solids are to be landfilled)
    - Co-composting.

5. Anaerobic Ponds

5.1 Introduction

Anaerobic conditions in waste stabilisation ponds develop if ponds receive high enough organic loads to cause depletion of dissolved oxygen (O_2) and fixed oxygen (e.g. NO_3 or SO_4). Furthermore, high organic loading rates may lead to the suppression of algae as oxygen suppliers. The highly loaded and, consequently, anaerobic ponds are often used as primary ponds in WSP systems treating wastewater in tropical countries.

Anaerobic processes are effective in warm climates as they can attain 60 - 85 % BOD removal in ponds designed for 1-5 days hydraulic retention time. Organic loading rates are substantially higher in anaerobic than in facultative ponds. This results in faster solids accumulation. Anaerobic ponds therefore have to incorporate sludge storage depths of 3 to 5 m. Their desludging intervals amount to 0.5 - 2 years, in contrast to facultative ponds whose desludging frequency may range from 3 - 10 years.

Given the frequently high organic strength of the faecal sludges, anaerobic ponds - with or without prior solids removal in separate settling units - are a feasible option for primary pond treatment. Use of facultative ponds for raw faecal sludges may often not be possible due to the high ammonia levels hindering algal growth (see Chpt. 6.2). Also, with the organic strength of faecal sludges being much higher than in wastewater, uneconomically large land requirements would result.

Fig. 8 contains a schematic drawing of a WSP system suitable to treat low to medium-strength faecal sludges. Such a system will normally comprise a series of one or more anaerobic ponds followed by a facultative pond. Maturation ponds will have to be added if the effluent is to be used for unrestricted irrigation.

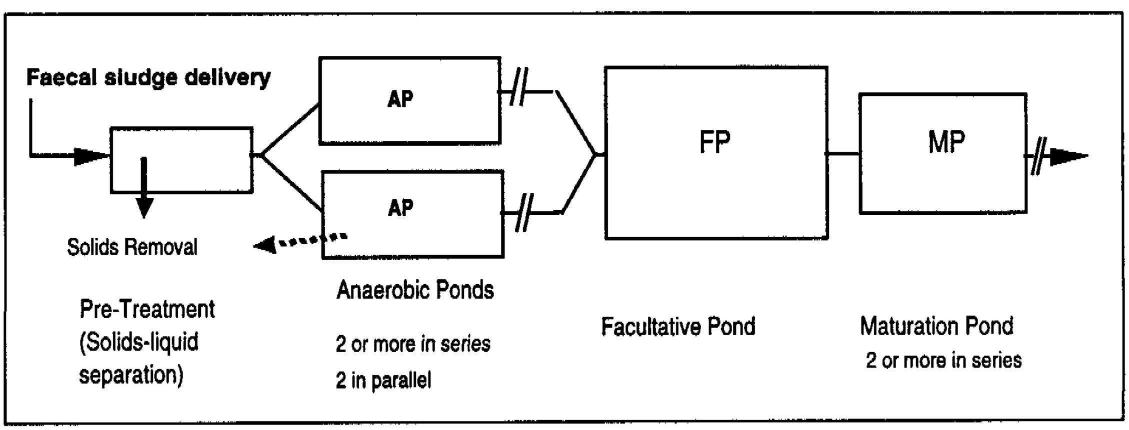


Fig. 8 Schematic Drawing of a WSP System Treating Low to Medium-Strength Faecal Sludges

Suggestions for further field research on FS treatment in anaerobic ponds deriving from this chapter are dealt with in Chpt. 9.

5.2 Inapplicability of Biokinetic Modeling to the Design of Anaerobic Ponds

Some authors have tried to determine kinetic models describing anaerobic substrate degradation and reactor design. Methanogenesis is the rate-controlling process in the anaerobic metabolism, comprising hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Braha (1988) suggested a varied order process model for anaerobic digestion of complex substrates. A model may prove feasible only if a number of conditions are satisfied:

1. As found in most industrial wastewater, a clearly defined biodegradable organic substrate has to be available. The substrate in ponds treating wastewater or faecal sludges is, in contrast, highly inhomogeneous both spatially and temporally. The ratio of dissolved vs. suspended organic matter and of non-biodegradable organic vs. biodegradable organic fraction is variable and can hardly be determined.

2. Composition and concentration of the active biomass have to be established. Where, for example, anaerobic filters are used to treat industrial wastewater, the system may comprise two separate steps, viz. a reactor for acidogenesis and one for methanogenesis. This allows the measurement of the active biomass in the respective biofilms. In ponds, however, the two anaerobic digestion steps occur concurrently, and the biomass is made up of a mixture of different types of bacteria responsible for anaerobic digestion. The biomass is partly located at the bottom of the pond and partly kept in suspension by the rising gas bubbles across the water layer.

Van Haandel and Lettinga (1994) conclude that a kinetic approach is in fact of very limited value for predicting anaerobic organic matter removal in a wastewater treatment process or for designing a system with a desired effluent quality. According to these authors, current knowledge about the kinetic theory of anaerobic digestion is not sufficient as a base for designing anaerobic treatment systems. Thus, the empirical approach of evaluating the observed experimental results when treating a specific waste is the only alternative to reaching optimal design variables for anaerobic digestion systems.

5.3 BOD Loading Rates for Anaerobic Ponds

Anaerobic ponds are normally designed on the basis of a temperature-dependent empirical value for the permissible organic loading rate. Land requirements will be lowest if the maximum possible BOD loading can be applied. The upper limit of the volumetric BOD loading is determined by odour emissions and minimum pH threshold value at which the anaerobic decomposition processes cease to work.

It is not possible to establish a commonly valid maximum BOD loading rate for anaerobic ponds at which odours will not become a problem. Formation of odour is strongly dependent on the type of waste to be treated in the plant, notably its sulphate (SO_4) concentration and volumetric loading rate, respectively. SO_4 is reduced to hydrogen sulphide (H_2S) under anaerobic conditions. H_2S is the compound mainly responsible for obnoxious odours. Other components besides H_2S and originating from the anaerobic decomposition of carbohydrates and proteins may contribute to obnoxious odours, too. Mara and Pearson (1986) propose a maximum sulphate volumetric loading rate of 500 g $SO_4/m^3 \cdot d$ (equivalent to 170 g $S/m^3 \cdot d$). At rates below this limit, apparently, critical SO_4 concentrations in the pond and, hence, the release of critical loads of H_2S can be avoided.

According to McGarry and Pescod (1970), a BOD loading of about 100 $g/m^3 \cdot d$ seems to form a thin aerobic surface layer in tropical anaerobic ponds treating municipal wastewater. This prevents the release of odorous gases from the anaerobic metabolism. However, 100 $g/m^3 \cdot d$ is a very low BOD loading rate and land use will consequently be high. In areas where odour control is important; i.e., near settlements, land costs are, however, often also high. Mara et al. (1992) suggest a volumetric BOD loading of 300 $g/m^3 \cdot d$ for anaerobic wastewater ponds at temperatures above 20 °C. An upper value of 400 $g/m^3 \cdot d$ is given to avoid odour emissions.

The sulphur content of human excreta is associated with the proteins excreted in the faeces. Daily per capita excretion of sulphur is diet-dependent and may on the average amount to 1.0-1.2 g S (Sawyer and McCarty 1967). At maximum organic loading rates of 300 g $BOD/m^3 \cdot d$ for temperatures >20 °C, associated sulphur loading rates would amount to 100 g $S/m^3 \cdot d$ (equivalent to 300 g $S/m^3 \cdot d$) , approximately. Hence, sulphur loading would remain below the above mentioned threshold level at which sufficient H_2S would be released to create noxious odours. In spite of the quantified criteria listed above regarding odour release, it is difficult to predict the presence of actual odour emissions and their perception by the neighbouring population at a particular site. The figures are speculative, and separate studies would be required using a mass balance model for the various sulphur forms and reactions across the pond.

H_2S and HS are in a pH and temperature dependent equilibrium. Concentrations of H_2S, which is the sulphur form responsible for odours, increases sharply as the pH drops below 7.5, phenomenon which may occur if an anaerobic pond is heavily loaded or overloaded (based on a BOD loading rate criterion). Sulphide may also impede methane production in anaerobic ponds if occurring at excess concentrations. The presence of heavy metals will lead to insolubilisation of sulphides (e.g. iron sulphides).

Since methanogenesis is the rate-limiting factor in anaerobic metabolism, products from the preceding acetogenesis reaction may accumulate and lead to a pH decrease. Optimum pH for methanogenesis amounts to 6.8 - 7.8. Based on various anaerobic digestion studies, McGarry and Pescod (1970) found that pH 6.0 probably constitutes the lowest limit for anaerobic tropical ponds. Determination of the maximum BOD loading rate beyond which pH is likely to drop below this threshold value is, therefore, important.

A study on anaerobic pond treatment of tapioca starch waste conducted by Uddin (1970) revealed that a volumetric BOD loading rate of around 750 $g/m^3 \cdot d$ resulted in a pond pH of 6.0. Fig. 9, which is based on Uddin's results shows that when the BOD loading rate was increased above this value, the volumetric BOD removal rate was reduced. Most likely, pond overloading impaired methanogenesis.

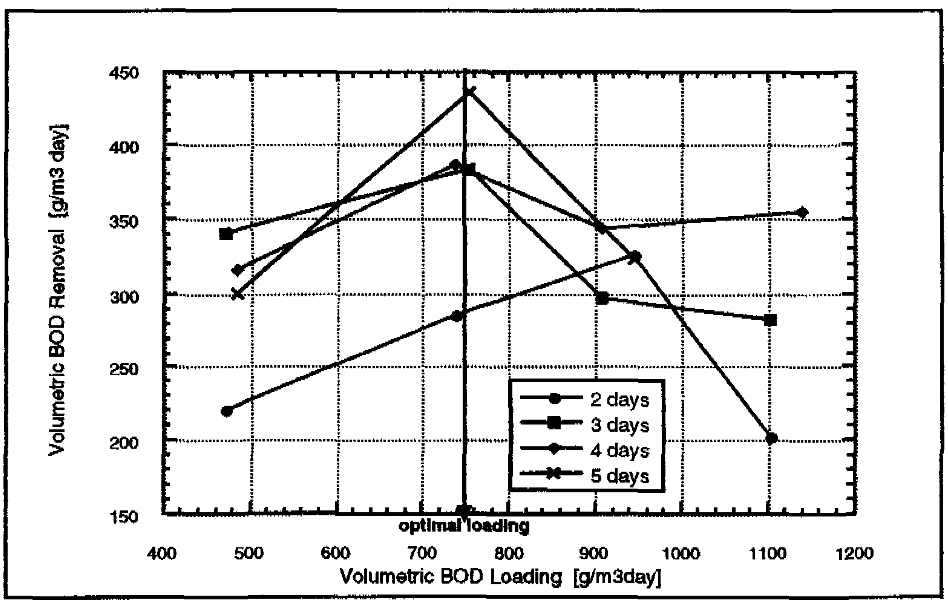


Fig. 9 Influence of Retention Time and Volumetric BOD Loading Rate on Volumetric BOD Removal Rate in Anaerobic Ponds Based on Uddin 1970 (Modified)

More practical research is required to establish the maximum safe loading rates for wastes such as septage and septage/public toilet sludge mixtures.
A 10-week investigation was carried out at the Achimota FSTP in Accra, Ghana in early 1994. The plant, which had already been in operation for four years, comprises two parallel batch-operated sedimentation/thickening tanks followed by four ponds in series, an aeration stack and further evaporation units. Usually, a mixture of public toilet sludge and septage is treated at this site. The average BOD loading rate of the primary anaerobic pond amounted to 165 $g/m^3 \cdot d$ only during this monitoring period (Larmie 1994). There was no indication of odour emissions at the relatively low BOD loading rate. The average pH amounted to 7.6 and points to a stable methanogenesis. Presumably, a much higher BOD loading rate could have been tolerated. However, increasing the number of vacuum trucks delivering FS to the plant was not possible within a useful time period.

Many trucks were, at the time, unloading their sludge at a sea disposal site, which required shorter haulage[1].

5.4 BOD and COD Elimination Rates

The published BOD elimination rates for anaerobic wastewater ponds range from 50 to 85 %. Temperature, retention time and BOD loading rate affect removal efficiency. Furthermore, the type of substrate; i.e., sewage, septage or public toilet sludge and its concentration influence the physical and biochemical processes.

To achieve high elimination rates at the start of a new operating cycle, some sludge should be left for seeding when emptying a pond. Experience with anaerobic pond treatment in tropical climate reveals that anaerobic digestion is basically completed after about four days (van Haandel and Lettinga 1994).

Highest BOD elimination and, thus, reduction of land requirements are attained by applying the highest permissible BOD loading rate (see Chpt. 5.3 on loading limits). Multi-stage anaerobic ponds, each operated at a maximum BOD loading rate, will, therefore, have the lowest land requirements. If the influent is of high strength[2], such as public toilet sludge without co-mixture of septage, removal rates (expressed in $g/m^3 \cdot d$) will be higher in a multi-stage pond than in a single anaerobic pond. When treating wastewater or faecal sludge of low strength[3], high BOD pond loading rates will lead to very short retention times. This may, in turn, cause a decrease in the BOD removal rate. Fig. 9, derived from data presented by McGarry and Pescod (1970) on work

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1 This is the type of limitation researchers are faced with when conducting field research at full-scale systems.

2 High-strength FS: BOD > 8,000 and COD ε 20,-50,000 mg/l (see also Table 2 for the strength-dependent classification of faecal sludges)

3 Low-strength FS: BOD < 2,000 and COD < 10,000 mg/l

performed by Uddin (1970), shows that the BOD removal rates for tapioca starch waste decrease at decreasing retention times, and increase to a threshold value if BOD loading rates are increased.

The question of **anaerobic treatability of septage** and its attainable BOD or COD elimination still remains unanswered. Such a treatment option could be of interest if septage and fresh faecal sludges, such as nightsoil or public toilet sludge, are treated separately to allow optimal treatment; i.e., tailored to each sludge type. Septage is usually stored for at least half a year to several years. Mara et al. (1992) argue that "anaerobic ponds are of no purpose as septage is already highly mineralised". Data on the organic content of the septage differ significantly. Figures published by Mara et al. (1986) for bottom sludge of septage tanks in warm climates show that the volatile solids content amounts to 40 - 50 % at temperatures of 26 - 28.5 °C. Strauss et al. (1997) published data for septage quality in tropical and temperate climates. Reported total volatile solids (TVS) values amount to about 60 % TS. The degree of mineralisation is not only dependent on temperature, but also on emptying frequency, sludge composition and on grease content. In many cases, septage is probably mineralised only partially during storage in the septage tank. Findings by the US EPA (1984) tend to support this assumption: anaerobic digestion of septage yielded TVS reductions of 30-47 %. Although attainable TVS reduction might be lower in anaerobic ponds than in anaerobic digestion tanks, the question of anaerobic degradability of septage in ponds does warrant further investigations. A first anaerobic stage might offer advantages even at moderate BOD and TVS reduction efficiencies, and may result in smaller land requirements than by directly feeding the septage into a facultative pond.

As mentioned in Chapter 5.3, the Achimota FSTP in Accra, Ghana, was monitored over a 10-week period in early 1994 after its start up in 1989. The overall BOD elimination (sedimentation/thickening followed by four ponds) amounted to about 80 %. The ratio of public toilet sludge to septage mixture load was 1:4 (Type A and Type B sludge, respectively). Development of BOD concentrations in the pond system is plotted in Fig. 10. The Figure also reveals anaerobic conditions throughout the pond system.

Mainly settable BOD was removed in the sedimentation/thickening tank. Anaerobic digestion in the liquid layer is not possible, as retention time is too short. In the first pond (8-9 retention days), anaerobic digestion proceeded until a low BOD concentration of 300-350 mg/l BOD was reached. Average elimination amounted to 75 %. For the particular mixture of faecal sludges, 300-400 mg BOD/l may constitute the lower limit of substrate concentration at which anaerobic digestion proceeds. SS elimination in the primary pond amounted to 17 % only as the sedimentation tank was well functioning and not overloaded.

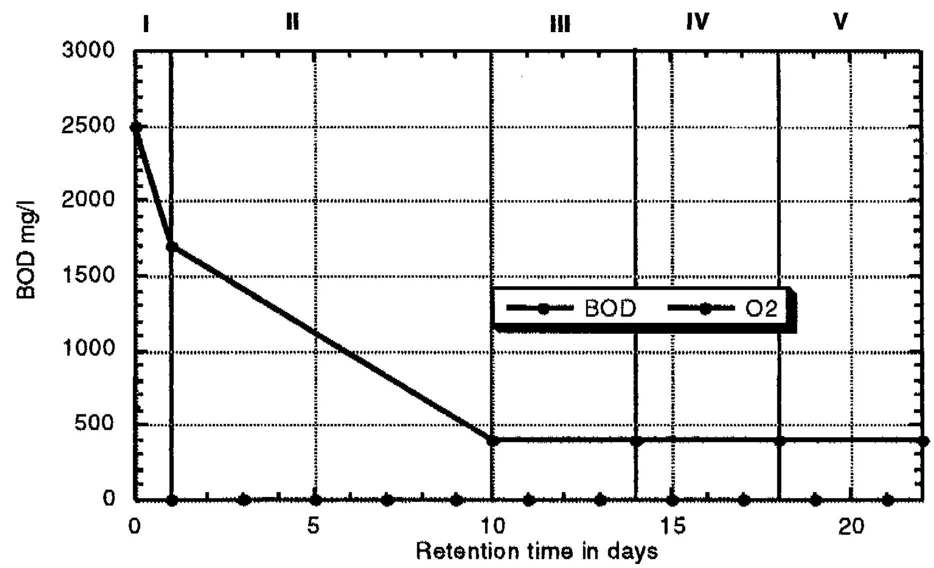


Fig. 10 BOD and Oxygen in the Various Treatment Units of the Achimota FSTP in Accra/Ghana. I: Sedimentation/ Thickening Tank; II: Primary Pond; III, IV, V: Ponds Designed as Facultative but Operating as Anaerobic Units (Results of a 10-Week Study Conducted in early 1994).

Further studies conducted in September 1997 revealed that the removal efficiency for unfiltered BOD was unusually high compared with results from other monitoring periods. This can be attributed to overfilled sedimentation tanks, which had not been emptied at the required frequency. Most of the sedimentation process, therefore, occurred in the ponds. This resulted in more essential BOD removals in the pond system, notably in the primary pond. BOD elimination across the system comprising settling tanks and four ponds in series amounted to 70 % and 85 % measured in filtered and unfiltered samples, respectively.

5.5 Ammonia Toxicity to Anaerobic Bacteria

In-depth investigations on the inhibiting effect of ammonia (NH_3) on anaerobic bacteria were not carried out in this study. Experiments conducted by Siegrist (1997) on the toxicity of NH_3-N for methane bacteria in digesters showed a 50 % growth inhibition at a NH_3-N/l concentration of 25-30 mg/l. The question whether these can be transferred to anaerobic ponds, including the adaptation potential of bacteria, remains to be examined. In the primary pond of the Achimota FSTP, average ammonium concentrations of 1,000 mg NH_4-N/l were measured. Average maximum air temperatures were 30 °C and an average pH of 8 was determined. Using Fig. 11, which shows the pH and temperature dependant relative shares of NH_4 and NH_3, the corresponding ammonia level amounted to 75 mg NH_3-N/l.

Slightly higher average NH_4-N concentrations of 1,100 mg/l were measured in a one-month monitoring cycle conducted in May 1997. COD elimination in the first pond was then observed to be as low as 10 %, whereas COD elimination increased to 35 % and 60 %, respectively, in the secondary and tertiary ponds. This contrasts with the results of the first study contained in Fig. 10 above. Anaerobic digestion seemed to have shifted from the primary to the subsequent ponds in which the NH_4-N concentration decreased to less than 1,000 mg/l. Although the database is still scarce, it can be assumed that strong ammonia inhibition in these ponds will occur at concentrations •80 mg NH_3-N/l.

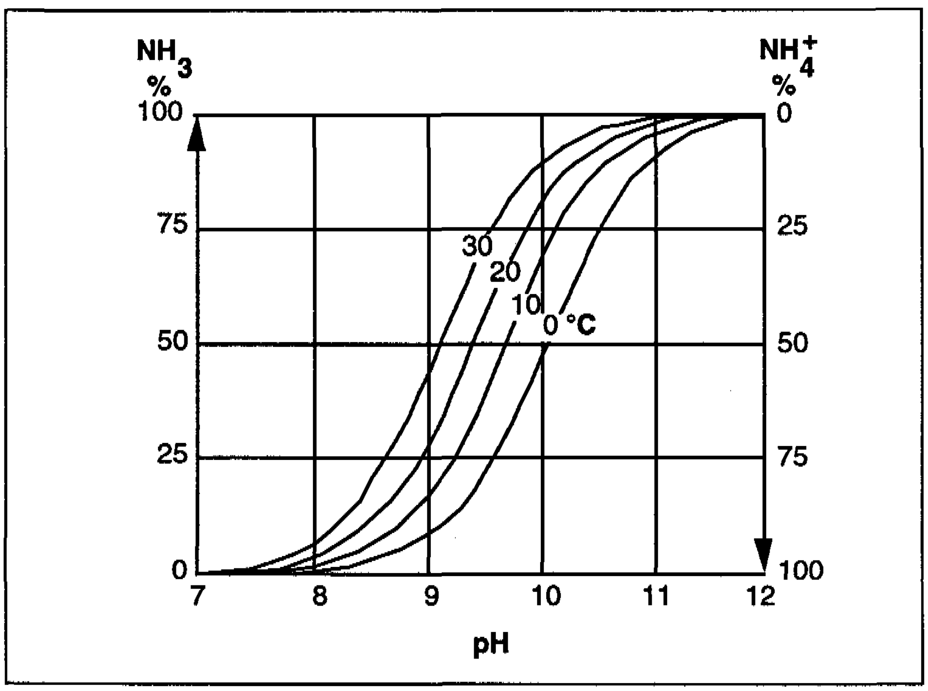


Fig. 11 NH_4-N and NH_3-N as a Function of pH and Temperature

5.6 How to Minimise Land Requirements

Estimated land requirements for two different pond treatment schemes were calculated on the basis of the findings discussed in this paragraph and given in Table 9. The required net surface area for treating septage by sedimentation-thickening and a facultative pond will be almost 50 % larger than if an anaerobic pond with an assumed 40 % BOD elimination is used ahead of the facultative pond. Even higher land savings would be achieved if the faecal sludge to be treated would be a mixture of septage and e.g. public toilet sludge. The BOD contained in the fresh, largely undigested public toilet sludge is easily degradable by anaerobic digestion and, hence, BOD elimination rates in the anaerobic pond of 70-80 % may be attained.

Table 9 Land Requirements for a Settling Tank/Pond System With and Without an Anaerobic Pond

Separate treatment of septage (Type B sludge) (initial BOD=1500 mg/l; TS = 15 g/l); maturation ponds are not included.

	Depth [m]	BOD loading rate	Assumed BOD elimination per treatment unit [%]	Required net area [m²]
Sedimentation tank + anaerobic pond + facultative pond	3 2 1-2	630 g /m²·d 300 g/m³·d 350 kg/ha·d	40 40 80	**13 L***
Sedimentation tank + facultative pond	3 1-2	630 g/m²·d 350 kg/ha·d	40 80	**19 L**

Pond BOD loading rates are the ones recommended by Mara (1992) for temperatures of 25 °C. The sedimentation tank loading is calculated for two tanks with a TS: BOD ratio of 10 and a TS loading rate of 6.3 kg/m² d (see Annex 2 for a design example).

* L = organic load (kg BOD/d)

5.7 Faecal Coliform and Helminth Egg Removal

A limited number of faecal coliform analyses were conducted as part of the Achimota FSTP monitoring campaigns of the four ponds arranged in series. The average nominal retention periods in the ponds are 9, 4, 4, and 4 days, respectively. All four units are working anaerobically. FC removal showed considerable variability. Average reductions amounted to one order of magnitude or log cycle in each of the ponds.

Only few helminth egg analyses were carried out on samples from pond effluents. Hence, no conclusions could be drawn from the data generated. There are indications though that considerable egg carry-over has occurred across the ponds during some of the monitoring cycles. This may be attributed to excessive solids accumulation in the first pond and to floating solids carry-over into subsequent ponds.

In wastewater ponds, 10-14 days retention time is in most cases sufficient to reach 100 % egg removal (Mara et al. 1992). A somewhat prolonged period is probably necessary in faecal sludge ponds, particularly when also treating fresh and undigested sludges. Buoyancy caused by the fermentation gases is likely to hinder the settling of helminth eggs and, hence, lead to prolonged egg suspension.

6. Facultative Ponds

6.1 Introduction

Facultative ponds allow aerobic BOD elimination as the pond is oxygenated mainly by the photosynthetic activity of algae and partly by wind (above all in large ponds). Such ponds also exhibit an anaerobic layer beneath the aerobic layer whose thickness is dependent on pond depth and organic loading rate. Facultative ponds have been in use for wastewater treatment for already quite some time. Years of experience on design, operation and maintenance is, therefore, currently available.

If faecal sludge is pretreated and the solids separated prior to the facultative pond, pond influent characteristics will be similar to those of raw municipal wastewater. Normally, this pond will be of the same design as wastewater facultative ponds, which are based on a temperature-dependent permissible surface BOD loading rate. The permissible loading rates at average temperatures of 20, 25 and 30 °C amount for example to 253, 350 and 440 kg BOD/ha·d, respectively (Mara 1992). Readers wishing to gain more insight into facultative pond design are referred to the pertinent literature (Arthur 1983; Mara and Pearson 1986; WHO/EMRO 1987). This chapter deals with specific problems of high ammonia concentrations in the supernatant of pretreated faecal sludge to be treated in facultative ponds. Solids-liquid separation and anaerobic FS treatment will generally provide insufficient treatment. Additional treatment is necessary as BOD concentrations in the effluents of anaerobic ponds treating FS are too high (200-400 mg/l) to allow discharge into receiving waters. Moreover, anaerobic pond effluents may not satisfy hygienic water quality standards - a relevant criterion if the effluent is to be used in agriculture or aquaculture, either directly or via a receiving water body.

This chapter is based on experience gained during the monitoring of the Achimota FSTP in Accra, Ghana.

6.2 Ammonia (NH_3) Toxicity to Algae

The Achimota FSTP, which was commissioned in 1989, comprises five ponds in series of which four were included in the monitoring programme. The effluent BOD concentration of the first pond amounted to about 320 mg/l. BOD elimination in the subsequent ponds was insignificant as shown in Table 10 (the data represent mean values of weekly measurements conducted over a period of ten weeks). No sign of measurable O_2 or algae growth has been observed thereby indicating that all four ponds were anaerobic, and that facultative pond conditions did not develop. Figures for the organic surface loading rate show that facultative conditions could theoretically have developed in ponds Nos. 2, 3 and 4. Permissible loading rates for facultative ponds range from 300-600 kg BOD/ha·day at temperatures of about 30 °C, depending on the empirical design model chosen (Mara et al. 1992). At the same time, influent BOD concentrations appear to have been too low to allow significant growth of anaerobic bacteria.

Table 10 BOD Loading Rates and BOD Elimination in the Pond Cascade of the Achimota FSTP (Accra, Ghana)

	Pond 1 (receiving settling tank effluent)	Pond 2	Pond 3	Pond 4
BOD loading kg/ha·d	1590 *	494	464	674
Elimination, %	78	• 0	• 0	• 0

* The loading rate for this anaerobic pond amounted to 165 g BOD/m^3·day

The high **ammonia** concentration was probably the cause for low biological activity. Under the conditions prevailing in the ponds of the Achimota FSTP (T = 30 °C; pH 8), ammonia (NH_3-N) amounted to 7.5 % of the measured ammonium (NH_4-N) concentration and, thus, to rather high concentrations (Table 11).

Table 11 NH_4-N and NH_3-N Values in the Pond Effluents of the Achimota FSTP, Accra (T = 30 °C; pH 8)

Effluent	**NH_4 + NH_3-N** mg/l (analysed)	**NH_3-N** mg/l (calculated)
Sed. tank	1,300	97
Pond 1	1,044	78
Pond 2	985	71
Pond 3	796	60
Pond 4	634	48

Kriens (1994) reviewed NH_3 toxicity for algae. Table 12 shows toxicity levels for some common and rather robust algae. Mara and Pearson (1986) point out that under certain conditions some algal species are able to adapt to and withstand concentrations of up to 50 mg/l ammonia. The high NH_4 concentrations, which were found in the ponds of the Achimota FSTP, are caused by sludges from public latrines exhibiting NH_4-N concentrations of 2,000 - 5,000 mg/l. They appear to be the cause of impairing algal growth. In contrast to the rather fresh and undigested public toilet sludge, NH_4-N concentration in septage amounts to 150 - 400 mg/l, only.

Table 12 NH_3 Toxicity for Algae (after Kriens 1994)

Algal species	Effect	NH_3-N, mg/l
Chlorella vulgaris	Hindered growth	6
Chlorella pyrenoidosa	79 % decrease in photosynthesis	31
Anacystis nidulans	77 % decrease in photosynthesis	31
Scenedesmus obliquus	88 % decrease in photosynthesis	31

For the reasons outlined above, BOD and NH_4 of public toilet sludges cannot be reduced further in facultative ponds. Facultative conditions simply do not develop and, therefore, call for special arrangements.

Deep anoxic ponds, which could be followed by facultative ponds, could be a good alternative to facultative ponds because they use much less land than conventional facultative pond systems (Almasi and Pescod 1996). However, also anoxic ponds only work if algae can develop in the surface layer. Thus, the problem of ammonia toxicity can not be solved by pond configuration alone.

7. Combined Treatment of Faecal Sludge and Wastewater in Waste Stabilisation Ponds

The problems described in this paper which may arise when treating faecal sludge in pond systems are also relevant for the combined treatment of FS and sewage in waste stabilisation ponds (WSP). Three critical variables should be considered when planning to co-treat wastewater and faecal sludge, viz. organic loading rate, solids load and ammonium/ammonia nitrogen concentration.

- **Organic loading rate:** Anaerobic and facultative ponds are sensitive to excessive organic (BOD) loading. In anaerobic ponds, the most serious symptomatic problem resulting from overloading is odour nuisance. In facultative ponds, it will impair the development of aerobic conditions and algal growth. The permissible additional faecal sludge load is dependent on the initial organic load exerted by the wastewater and on the loading rates for which the ponds were originally designed.

- **Solids load:** Ponds may fill up at undesirably fast rates due to high solids contents in FS. Options for pretreatment of FS are described in Chpt. 4. Separation of the FS solids prior to treating the liquid in wastewater stabilisation ponds contributes to optimum WSP performance and to minimising short-circuiting and sludge removal operations.

- **Ammonia nitrogen:** The maximum NH_3 concentration tolerated by the algae in the facultative pond is an additional factor influencing the permissible FS load in a WSP system. Under the conditions prevailing in facultative ponds in tropical climates (T • 25-28 °C; pH 7.5 - 8), ammonia (NH_3) amounts to 2-6 % of the ammonium (NH_4) concentration. If the permissible NH_3-N concentration in facultative ponds is set at 20 mg/l, and assuming that 5 % of NH_4 are NH_3, the maximum NH_4-N concentration of the combined waste in the influent to the facultative pond amounts to 400 mg/l. The bulk of the septage, usually stored for a period of up to several years, does not exhibit very high NH_4-N concentrations. Fresh FS such as public toilet sludge, however, may contain NH_4-N concentrations of up to 5,000 mg/l.

Based on measured or assumed ammonia concentrations, the permissible volumetric FS loading rate in the pond influent (% share) can be calculated according to the following formula:

$$\mathbf{FS\ [\%]} = \frac{100}{\frac{C_{FS}-400}{400-C_S}+1}\ ,\ \text{where:}$$

FS (%) permissible volumetric FS loading as percent of total *influent*

C_{FS} NH_4-N concentration in the anaerobically pretreated FS (mg/l)

C_S NH_4-N concentration in the untreated wastewater (mg/l)

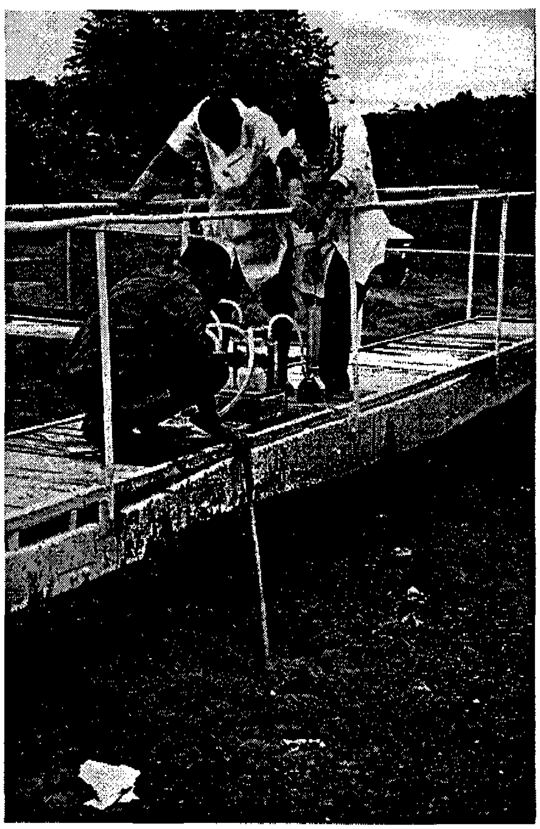
Co-treatment of wastewater and faecal sludge in waste stabilisation pond systems and in activated sludge plants is discussed further in Heinss (1998).

8. Recommendations for Preliminary Design

8.1 Introduction

Design principles and preliminary design guidelines for solids-liquid separation and pond treatment of faecal sludges are presented below. The recommendations are based on collaborative field research conducted in Accra, Ghana. This comprised the full-scale treatment of septage/public toilet sludge mixtures in settling/thickening tanks and anaerobic ponds. In another part of the study, septage/public toilet sludge mixtures, public toilet sludges and primary pond sludges were treated in pilot-scale sludge drying beds. Furthermore, information obtained from scarcely published literature dealing with faecal sludge treatment, as well as the state-of-the-art knowledge on wastewater treatment in stabilisation ponds has been taken into consideration.

First, design principles are discussed, followed by suggested design guidelines.



Sludge Sampling from Different Layers in a Settling/Thickening Tank

Design principles and preliminary design guidelines for the treatment of faecal sludges in anaerobic and facultative stabilisation ponds and suggestions regarding solids-liquid separation in settling/thickening tanks (as a pretreatment ahead of ponds) and in sludge drying beds are based on collaborative field research conducted in Accra, Ghana.

8.2 Recommended Design Principles

8.2.1 Solids-Liquid Separation Prior to Pond Treatment

It is recommended that **low-strength (Type "B")** sludges such as septage or mixtures of low and high-strength sludges be subjected to solids/liquid separation by sedimentation/thickening or in sludge drying beds prior to pond treatment. Substantial solids removals may be attained, resulting in considerable land savings for the overall treatment works. Furthermore, the technical and operational problems associated with the emptying of large quantities of sludge from primary ponds can be avoided.

Solids/liquid separation is also strongly recommended if FS is to be co-treated with wastewater in waste stabilisation ponds.

To treat a given flow of faecal sludges, drying beds require a considerably larger area than settling/thickening tanks. However, less area would be required to treat the drying bed percolate than the settling tank supernatant. A comparison of the two options is discussed in Chpt. 4.5. The selection of the "best" process is determined by practical aspects related to sludge removal operations, dewaterability and settleability of a specific FS, land requirements /availability, local meteorological conditions, and to the extent of additional treatment required to achieve the desired effluent and sludge (solids) quality. For the examples presented in the design summary (Annex 1), settling/thickening has been assumed as the preferred option.

High-strength, i.e. fresh and mostly undigested sludges **(Type "A" sludges)**, are hardly conducive to solids/liquid separation. This is not surprising as experience with the dewatering of sewage treatment plant sludge shows that digested sludge is more readily dewaterable than fresh sludge. Dewatering rates for Type A sludges are low and periods for dewatering and drying tend to be much longer (up to several weeks) than for septage/public toilet sludge mixtures or primary pond sludge. It can be assumed, though, that high-strength sludges may become moderately dewaterable if stored for over a month.

Type "A" sludges are by themselves not suitable for solids-liquid separation in separate sedimentation tanks as the already high solids concentration (35-55 g TS/l) prevents sedimentation of settleable particles ("hindered settling").

8.2.2 *Separate Treatment of High and Low-Strength Faecal Sludge*

Treating high and low-strength faecal sludges separately may prove advantageous, particularly if, in a specific city, appreciable amounts of high-strength FS are produced.

The recommendations presented below as to what we think may constitute sustainable treatment options for **high-strength (Type "A")** sludges are based on our engineering judgement, and inferences drawn from reported experience and own observations. Except for the collaborative field tests carried out by WRI in Accra, Ghana, with drying bed treatment of public toilet sludges (see Chpt. 4.3), SANDEC has not undertaken own field research covering the separate treatment of high-strength sludges yet.

Based on current experience, FS consisting exclusively of Type "A" sludges are not conducive to **pond treatment** in the same way as are lower strength sludges or wastewater. Solids separation will occur only after the sludges will have become fully or almost fully digested. For this, extensive retention periods would be necessary. These may be as long as 15-30 days, depending on ambient temperatures. Evaporative losses might accordingly be substantial, resulting in reduced effluent flows.

In contrast to such ponds, hydraulic retention of 5-8 days only is required in anaerobic ponds treating low to medium-strength sludge mixtures. Ammonia (NH_3) concentrations in Type "A" sludges are high. This may lead to ammonia toxicity for the anaerobic bacteria, hence to inhibition or retardation of the digestion process. Ammonia levels may be diminished, though, through extended pond storage and gradual release of NH_3 gas. Ponds devised to treat Type "A" sludges using the long retention periods required for complete anaerobic digestion are likely to accumulate an excessive mass of separated solids. Pond emptying and further/storage drying of the removed solids will therefore pose a particular challenge. This must be duly considered in plant design, site arrangements and operational management.

Anaerobic digestion[1] in digester tanks with biogas utilisation followed by dewatering in **sludge drying beds** would, from a technical viewpoint, constitute a more feasible option to treat Type "A" sludges, although some of the factors listed above would equally apply to this technology. Closed reactors in which the gas is collected and stored are subjected to overpressure. Hence, the CO_2 pressure in the sludge chamber is likely to be higher than in

1 Anaerobic digestion of faecal sludge is not covered in this document but may be dealt with in a forthcoming discussion paper.

ponds open to the atmosphere resulting in a lower sludge pH and, hence, in lower NH_3 concentrations than in anaerobic ponds. A reduced risk for ammonia toxicity would thereby result.

Ideally, anaerobic digesters should be equipped with mixing devices to ensure optimum conditions for the biochemical processes. Yet, mechanised digesters may, in many situations, not constitute sustainable technology as it implies the use of capital-intensive installations and skilled operating personnel. However, there is, in developing countries, often a shortage of well-trained personnel particularly so in the public sector. Experience to date shows that anaerobic digestion tends to be an option more sustainable on a small scale such as on farms or for unsewered public toilets[1]. SANDEC has not conducted field research on this alternative to date, but may initiate respective fieldwork in future.

Bucket latrine sludge was **co-composted** with municipal refuse in Rini near Grahamstown, South Africa, for a number of years[2]. Inferring from own observations, the scheme appeared to work well, technically. We can not, however, judge its long-term economic and social sustainability as no respective information has been published so far. The treatment option may constitute a future subject of SANDEC's collaborative field research activities.

Low-strength (Type "B") or mixtures of low and high strength faecal sludges may be treated by solids-liquid separation followed by a series of stabilisation ponds.

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1 An example of the small-scale digestion option exists in India where Sulabh International, an India-based NGO, builds and operates public toilets to which digester units with gas holders are attached. The choice between decentralised (or even localised) and centralised FS treatment depends on the type of sanitation systems currently in use or planned for. Treatment on a smaller scale calls for a different urban sanitation stratify than if all faecal sludge is collected for treatment in centralised plants. Respective decisions, therefore, must be made on a planner's level rather than on the level of treatment process selection and technical design.

2 The scheme was abandoned as the bucket latrines were reportedly replaced by a sewerage system.

8.3 Design Guidelines

8.3.1 Settling/Thickening in Batch-Operated, Non-Mechanised Units

Sizing

A complete settling tank design example is contained in the Annex 2.

The decisive design variable for settling/thickening tanks treating faecal sludge is the required **sludge storage volume**. The calculated tank volume has to be verified to ensure minimum liquid retention time in the tank's clear/settling zone. The sludge storage volume for the type of tanks used at the Achimota FSTP, Accra (rectangular tanks, batch cycles of several weeks, access ramp for stored sludge removal by front-end-loaders), can be calculated on the basis of the attainable thickening concentration in the settled and floating sludge, and on the desired duration of the operating cycle. The required tank dimensions may be obtained by assuming four distinct zones (see also Fig. 12 below):

- **Scum:** ~ 0.8 m
- **Clear water zone:** ~ 0.5 m
  A minimum liquid retention period of 3 hours is required in this zone
- **Separation and storage zone:** ~ 0.5 m
- **Thickening zone:** To be calculated on the basis of the attainable sludge solids concentration (approx. 150 g SS/l for the septage and public toilet sludge mixture treated in Accra); the SS concentration in the incoming sludge mixture and the desired tank operating cycle

Sedimentation and thickening tests should be performed with 1 or 2-litre cylinders and with the expected future type of sludge mixture prior to final sizing of the sedimentation/thickening tanks. In the investigations carried out in Accra in 1-litre cylinders, the SS concentrations in the clear water zone and settled sludge closely corresponded with the results obtained on the full-scale sedimentation tank. The SS concentration in the scum was higher in the sedimentation tank due to the influence of sun drying (Heinss et al. 1998).

Tank Geometry; Structural and Operational Measures

Minimising short-circuiting is of prime importance for optimum performance of the sedimentation/thickening units. It is the hydraulic flow pattern which influences to a large extent the position and clarity of the clear water zone and, hence, the quality of the outflowing supernatant. The inlet and outlet zones must be properly designed and positioned. The inlet zone should be constructed in such a way as to distribute the potential energy of the sludge discharged from the trucks. This will prevent a circular flow pattern and, hence, disturbances of the sedimentation process.

From a hydraulic viewpoint, the settling/thickening tanks should be long and narrow; i.e., with a width to length ratio of 1 : 5 to 1 : 10.

Structurally, the following details should be observed:

a) To prevent the carry-over of solids:

- If the outlet is placed at the deep end of the tank, it must be positioned in the clear water zone; i.e., under the scum and above the sludge storage zone. On account of the varying depth of the clear water zone, it would be useful to equip the outlet with an adaptable and variable draw-off level.

- Alternatively, the outlet may be placed away from the deep end in order to minimise solids carry-over into the effluent.

- The outlet collection channel or pipe should extend over the entire width of the tank to ensure optimum flow conditions.

b) To minimise short-circuiting:

- Installation of a stilling grid or other devices to distribute the energy of the FS discharged from the trucks.

The following **operational measures** allow optimisation of the tank's hydraulic behaviour:

- The outflow of the settling tank could be interrupted during the day and reopened only after the tank's content has settled down. In this way, an effluent from the undisturbed clear water zone could be obtained. A freeboard will be necessary for the storage of a daily tank load (e.g. 0.5-1 m for the described tanks). It would only work if the staff were willing to open and close the outflow pipe once a day, preferably in the morning before the vacuum trucks start arriving. Such tank would have to be equipped with an overflow.

- For raw sludge discharge, the hose of the vacuum truck should be lowered to a level just above the thickening zone (at a depth of about two metres).

Detailed results on the monitoring of the batch-operated settling tanks operated in Accra, and suggestions for improved design are contained in a forthcoming SANDEC publication (Heinss et al. 1998). Fig. 12 illustrates an improved sedimentation/thickening tank design with a ramp allowing access by front-end- loaders for sludge removal. Such tanks should be loaded at the deep end through a sludge delivery chamber to allow maximum amounts of solids to be retained and accumulate at the deep end. A dash plate would cater for energy distribution. Effluent draw-off would occur at the tank's shallow end. A scum holder as shown in Fig. 12 would separate the scum from the effluent. It should be constructed such as to allow easy access for front-end-loaders for the removal of the separated solids. A suitable effluent arrangement may consist in submerged troughs attached to the tank's sidewalls and adjustable in height.

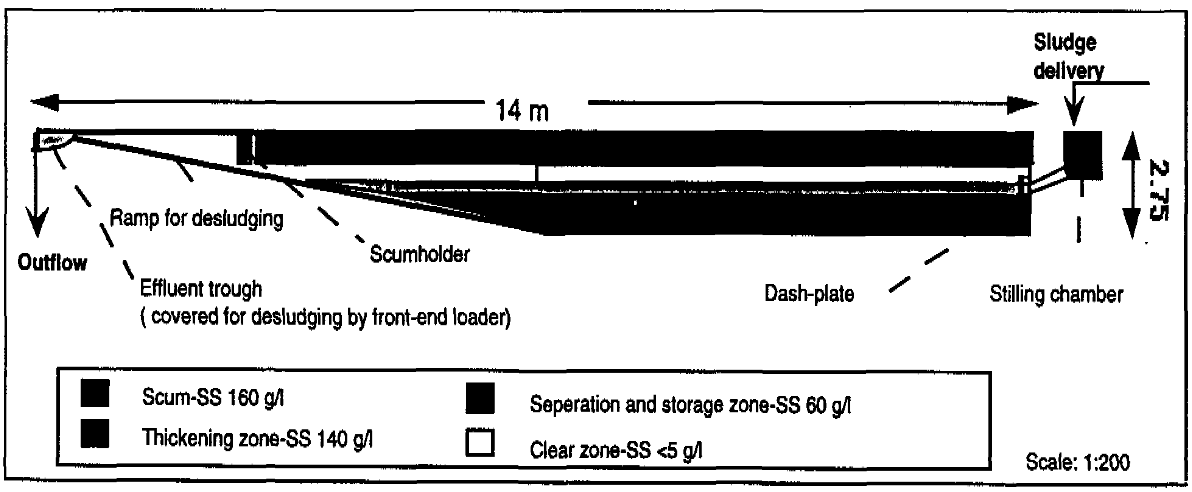

Fig. 12 Improved Design of a Sedimentation/Thickening Tank Providing Storage for approx. 50 t of Suspended Solids (Desludging by Front-End Loader)

The following minimum **removal performance** may be expected with the type of settling/thickening tanks described above, and operating cycles comprising four weeks of loading and four weeks of resting:

- BOD and COD: 50 %
- Susp. solids: 60-80 %
- Helm. eggs: 50 %

8.3.2 Unplanted Drying Beds

Sludge application or loading depths should amount to max. 30 cm. With solids loading rates of 100-200 kg $TS/m^2 \cdot yr$, 40 % TS contents in the dewatered sludge may be attained within 8-12 days. The dewatering/drying rate depends on the type of sludge and its solids content, weather conditions (temperature, rainfall, wind), loading rate, application depth, and on the operating "age" of the bed (greater filter efficiency is obtained with increasing number of loadings). The hygienic quality of the dewatered or dried sludge (best expressed by the residual concentration of nematode eggs) is dependent on the combined effect of time, dryness and temperature. Complete helminth egg inactivation can be achieved if the sludges are allowed to dry over several months or if the water content of the drying sludge drops to less than 5 %. This extended storage/drying process will, in most cases, have to be conducted outside the sludge drying beds in order to economise on land use and investment costs of the beds. Sludges undergoing this type of treatment are suitable for unrestricted agriculture use.

Dewatering is attained by both evaporation and seepage. During dry weather, the sludges may give off 75-95 % of their water within five days, and seepage is expected to cease after 8-10 days, except with public toilet sludges which may release water over a period of up to 2-3 weeks. The drained liquid will amount to 50 - 80 % of the raw sludge volume load on the beds. Substantial reductions of suspended solids (• 95 %); COD (70-90 %) and helminth egg counts (100 %) are achieved in the percolating liquid. Inorganic nitrogen (NH_4-N; NH_3-N) removal may range from 40 to 60 % and is caused by the combined effect of nitrification and ammonia stripping. Waste stabilisation ponds may present a suitable treatment option to further reduce the organic load, ammonium and pathogens to meet the required quality standards for discharge or reuse. The drained liquid may be treated separately, in combination with municipal wastewater or with the supernatant from a sedimentation/thickening unit treating low to medium strength (Type "B" or mixtures of Type "A" and "B") faecal sludge.

8.3.3 *Anaerobic and Facultative Ponds*

Anaerobic ponds: BOD loading and removal rates of 165 and 130 $g/m^3 \cdot d$ respectively, observed in the first pond of the Achimota FSTP (Accra), probably constitute rather conservative values. Based on the BOD loading rates in the settling tanks of this plant, and from conclusions drawn from data published by Uddin (1970), McGarry and Pescod (1970) and Mara et al. (1992), it is assumed that significantly higher loading rates could be applied.

We tentatively recommend that **anaerobic ponds** for faecal sludge treatment in tropical climates should be designed with a BOD loading rate of **350 $g/m^3 \cdot d$.** This value is likely to be safe and will prevent a pH drop to less than 6 as well as odour emissions. Additional investigations are required to explore the feasibility of higher loading rates.

BOD elimination rates of 70-80 % can be achieved in a single anaerobic pond when treating septage/public toilet sludge mixtures. 3-4 days of hydraulic retention appear to be sufficient. Faecal coliform removals of one order of magnitude (log cycle) may be assumed for each anaerobic pond in a pond series. For 100 % helminth egg removals, retention periods of 2-3 weeks may have to be provided, including both anaerobic and facultative ponds.

Settling tank operation may not always be optimal. Primary anaerobic ponds treating the settling tank supernatant are therefore expected to receive varying loads of settleable solids. Such ponds require emptying more frequently (possibly every 2-3 years) as they might accumulate more sludge than primary facultative ponds. They should, therefore, be equipped with a ramp to allow vehicle access.

Facultative ponds: Facultative ponds treating the liquid fraction of faecal sludges or mixtures of faecal sludges or their liquid fraction with wastewater, should, in principle, be designed according to the established design practice for waste stabilisation ponds. They should receive liquids not exceeding 600 mg BOD/l and 20-30 mg NH_3/l. Depending on the minimum monthly temperature, organic loading rates ranging from 350 kg/ha·d (25 °C) to 400 kg/ha·d (28 °C) should be used (Mara et al. 1992). Where ammonium levels > 400 mg/l are to be expected, measures must be taken to avoid ammonia (NH_3) toxicity to algae and to enable facultative pond conditions. Co-treatment or dilution with municipal wastewater might be a feasible option. Else, the inlet portion of the facultative pond may be intermittently aerated to induce nitrification and, hence, reduction of NH_3. To our knowledge, this option has not been tested before and would therefore warrant specific field research. Further options are described in Chpt. 9.4 below.

9. Needs for Further Field Research

9.1 Introduction

In spite of four years of field research conducted with full and pilot-scale faecal sludge treatment plants in Ghana, several questions remain unanswered. Moreover, both in-depth field research conducted to date and practical situations faced by planners and engineers have led to new researchable questions. What follows below is a list of subjects justifying further field and/or action research. Emphasis is, thereby, laid on specific aspects related to the treatment processes described in this report.

Field research should certainly also be conducted on options other than the ones examined here. They, too, may constitute sustainable solutions for treating faecal sludges in developing or newly industrialising countries. Respective research needs are, however, not dealt with here.

9.2 Solids-Liquid Separation

Sedimentation/Thickening

The type of batch-operated settling/thickening tank currently in use in Ghana constitutes a sensible option in areas with a low degree of mechanisation. As shown by the investigation, however, tank design, geometry and operations should be altered to improve its performance. Several issues warrant further field research:

- Optimum tank design and geometry to ensure smooth operation and improved solids separation
- Removal operations for settled and floating solids where use of front-end-loader and admixture of sawdust are not possible (e.g. using sludge hoppers and gravity siphoning of separated solids)
- Use of primary anaerobic ponds to accommodate solids separation and thickening; rate of solids separation as a function of organic stability (degree of digestion).

Sludge Drying Beds

The following researchable issues have been identified regarding the use of unplanted and planted sludge drying beds:

- Threshold levels for raw FS solid contents beyond which drying bed treatment becomes unsuitable

- Additional pilot-scale drying bed experiments with varying types of FS to establish performance and design criteria more firmly; assessing the impact of rainfall at various stages of the drying process

- Comparative studies of unplanted vs. planted sludge drying beds.

9.3 Anaerobic Ponds

A number of issues related to anaerobic pond treatment of FS warrants further research and comprise:

- Maximum BOD loading rates to avoid odour development and ensure safe anaerobic degradation; establishing the minimum pH threshold to guarantee safe fermentation

- Ammonia (NH_3-N) threshold levels to avoid toxicity to anaerobic bacteria; extent of bacterial adaptability to high levels of ammonia; methods of reducing ammonia levels (see Sect. 9.4 below)

- Retention period in ponds or digester tanks vs. degree of organic stability (degree of digestion) vs. solids separability in high-strength sludges such as bucket latrine and public toilet sludges

- Helminth egg removals as a function of raw FS characteristics (fresh vs. pre-digested), pond loading rates and pond emptying frequency

9.4 Facultative Ponds

Treating the supernatant liquor of medium to highly concentrated sludges in facultative ponds will usually be associated with ammonia inhibition of algae. Therefore, specific measures should be developed and tested to reduce ammonia levels to below the critical threshold levels. The following options may prove feasible under specific conditions and hence justify testing and assessing:

- **Diluting** the concentrated liquid with river water or wastewater to reduce the ammonia concentration to harmless levels for aerobic bacteria and algae. Combined treatment of high-strength (Type "A") faecal sludges and wastewater may, therefore, be effective under specific conditions (see also Chpt. 7).

- **Cascade stripping** of NH_3

  This is a theoretical option and its effectiveness may be limited. Application can be considered where the topographic conditions prove suitable and pumping is not required.

- **Surface aerating** the inlet section of the first facultative pond. This may result in the following effects:

  - Ammonia (NH_3) stripping
  - Growth of nitrifying bacteria (such as *Nitrosomonas* and *Nitrobacter*) oxidising ammonia into nitrate
  - Development of algae due to a decrease in ammonia concentration
  - Oxygen production by algae

  Aeration may probably be intermittent as it serves only to secure stable aerobic conditions. Optimum aeration intervals, system performance and technical and economic sustainability should be determined. Aeration systems requiring electric power supply may not be possible in a number of places. Photovoltaically powered aerators may, therefore, be used. Such systems are already being applied in a number of ponds and lakes in the United States.

Furthermore, treatment of septage in facultative ponds should be examined to find answers to the following questions:

- Aerobic biodegradability of septage
- Pond performance and design to meet nutrient and hygienic effluent standards
- Sulphur levels in faecal sludges and role of sulphur (H_2S) in algal growth inhibition.

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ANNEXES

Annex 1 Preliminary Design Guidelines

(Summary)

Note:

1. The design guidelines provided below are based on the assumption that the treatment units are properly operated and maintained, and that the suggested operating cycles comprising loading, consolidation and emptying of sludge drying beds, settling/thickening tanks and anaerobic ponds, are adhered to.

2. Facultative ponds may have to be complemented by maturation ponds. Size and number of these ponds are dependent on the effluent quality required to satisfy hygienic standards, mainly.

A1.1 Treatment of High-Strength (Type "A") Faecal Sludge

- Type "A", i.e. fresh and largely undigested faecal sludge is not or only hardly conducive to the treatment options described in this document. Solids-liquid separation is inhibited due to the undigested nature of the sludge. Its high ammonia concentration is likely to cause ammonia toxicity for anaerobic bacteria in anaerobic ponds or digesters, and for algae in facultative ponds. Hence, anaerobic digestion rates may remain low, and facultative pond conditions are unlikely to develop.

- The following treatment options warrant consideration:

  a) ***Anaerobic digestion* or anaerobic pond treatment + *drying beds*** complemented by ***pond treatment*** for the digester supernatant and the percolate.

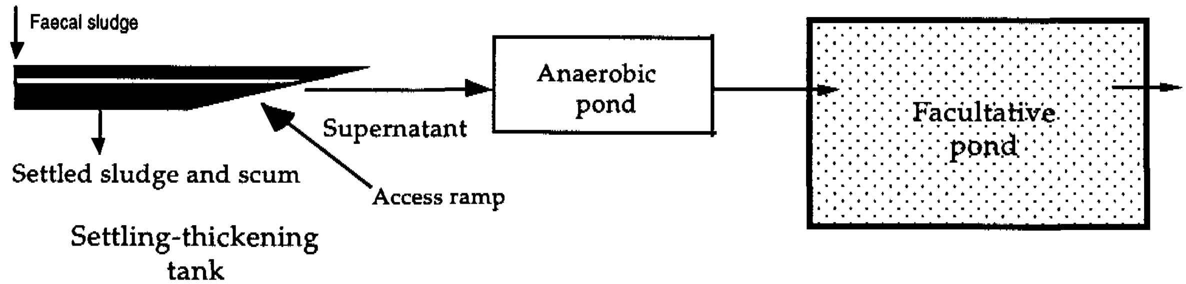
     In developing countries, anaerobic digestion constitutes a sustainable technology as a *small-scale* option, mainly. Its use at the scale of centralized urban treatment plants, however, may not yet be sustainable in many situations as it implies the use of capital-intensive, mechanized installations and skilled operators.

     Pond treatment of high-strength sludges may be an alternative to the use of digester tanks with gas utilization if long retention periods of 15-30 days can be guaranteed. Solids accumulation rates in primary anaerobic ponds might be considerable. Sludge removal from the pond must be ensured and ammonia toxicity risks taken into account. Evaporative losses may be substantial due to the long retention periods to be observed. Relatively small effluent flows may therefore result. As a result, such ponds may function as storage and evaporation ponds, mainly.

  b) ***Co-Composting*** with suitable organic bulking material, such as domestic refuse or woodchips.

c) If, in a particular urban setting, only relatively small amounts of high-strength sludges are produced relative to other types of FS and to wastewater, ***co-treatment*** with low-strength (Type "B") faecal sludge (ref. Chpt. 9.2 below), with wastewater (ref. Chpt. 5) or in an anaerobic digestion system of a sewage treatment plant may prove a feasible option.

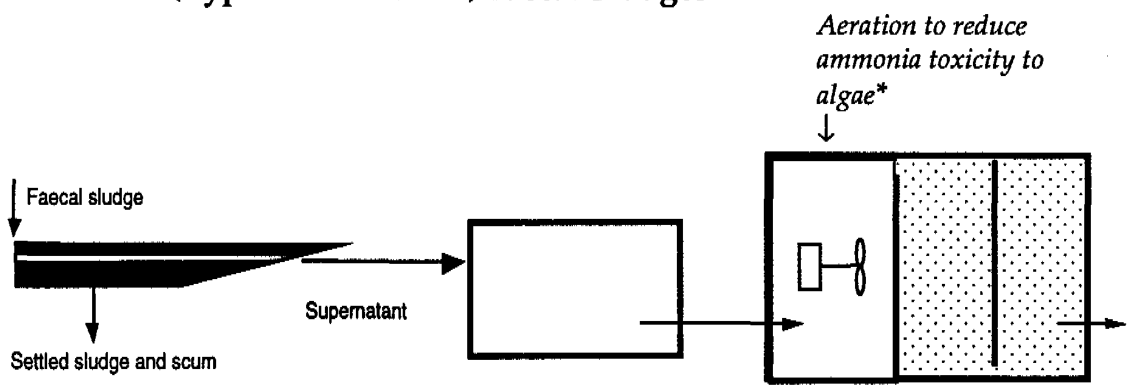
A1.2 Treatment of Low-Strength (Type "B") Faecal Sludge



Batch-operated sedimentation /thickening tank	Anaerobic pond	Facultative pond
Assumed operating pattern: 8-week cycle (4 weeks loading + 4 weeks quiescent sludge consolidation; 6 cycles per year); two parallel settling tanks Attainable TS content: 15% Tank sizing (see the Annex for a design example) is based on the desired storage capacity to be provided for settled and floating solids Liquid retention: • 4 hours in the clear/settling zone Attainable contaminant removal in the percolating liquid: - BOD and COD: 50 % - SS: 60-80 % - Helminth eggs: 50 % Separated solids (sludge) to be further treated (e.g. by co-composting or drying bed treatment + storage) prior to use in agriculture or to landfilling	Tentative guideline: B_V = 200 .... 350 g/m^3·day * for design temperatures varying from 15 to 25 °C (based on the design for anaerobic wastewater ponds, Mara 1997) —— (B_V = Volumetric BOD loading rate)	BOD elimination: 80% Retention time: > 5 days L_a = 170 .... 350 kg/ha·day, for design temperatures varying from 15 to 25 °C (Mara et al. 1992) —— (B_a = Surface BOD loading rate)

* Anaerobic pond loading limits still require in-depth investigation. It is hypothesized that higher volumetric organic loading rates might be tolerated for high-strength wastes than for wastewater (McGarry and Pescod 1970).

A1.3 Treatment of Mixtures of High and Low-Strength (Types "A" and "B") Faecal Sludges



Settling/thickening tank | Anaerobic pond | Facultative pond

* *Note: **Alternatively, the settling tank supernatant may be co-treated with wastewater, to reduce ammonia to levels non-toxic to algae.***

Sedimentation tank (Alternatively, type "A+B" mixtures may also be treated in sludge drying beds)	**Anaerobic pond**	**Facultative pond**
Assumed operating pattern: 8-week cycle (4 weeks loading + 4 weeks resting; 6 cycles per year); two parallel settling tanks Attainable TS content: 15% Tank sizing (see the Annex for a design example) is based on the desired storage capacity to be provided for settled and floating solids Liquid retention: • 4 hours in the clear/settling zone Attainable elimination: - BOD and COD: 50 % - SS: 60-80 % - Helminth eggs: 50 %	BOD elimination: 70-80 % Retention time: 3-4 days Tentative guideline: B_v = 200 .... 350 g/m^3·day * for design temperatures varying from 15 to 25 °C (based on the design for anaerobic wastewater ponds, Mara 1997) * Tolerance for higher loading rates still to be tested) ——— (B_v = Volumetric BOD loading rate)	BOD elimination: 80% Retention time: > 5 days L_a = 170 .... 350 kg/ha·day, for design temperatures varying from 15 to 25 °C (Mara et al. 1992) To support the development of nitrifying bacteria and the development of facultative conditions intermittent aeration at the pond inlet area may be considered. ——— (B_a = Surface BOD loading rate)

Annex 2

Design Example for Solids-Liquid Separation and Pond Treatment of Faecal Sludges

Problem

In a town in West Africa, 133,000 people use on-site excreta disposal systems. Thereof, 7,000 use public toilets and 126,000 are connected to septic tanks. It is supposed that vacuum trucks collect all faecal sludge. A pond system for treating the collected faecal sludge shall be designed. The FS shall be pretreated in sedimentation/settling tanks, which are to be operated on cycles of one month of loading followed by one month of consolidation prior to desludging. The effluent of the tanks shall be treated in one or more anaerobic ponds followed by facultative ponds. FS analyses have yielded the average TS and BOD concentrations listed below. The average yearly minimum temperature is 25 °C.

Sludge Characteristics and Load Calculations

Volumetric Load

Table 3 may be used to estimate the volumetric load if no reliable site-specific figures on collected FS quantities are available. Assume:

For septage:	1 l/cap·d
For public toilet sludge:	2 l/cap·d

➔ V_{load} = (7,000 x 2 l/cap·d) + (126,000 x 1 l/cap·d) = <u>140 m³/d</u>
The septage : public toilet sludge volumetric ratio amounts to 1:9

Solids Load

Septage	TS = 18 g/l	➔ 21.4g/l for the 1:9 mixture
Public toilet sludge:	TS = 52 g/l	

TS_{load} = 140 m³/d x 21.4 g/l = 2996 kg/d • <u>3,000 kg TS /d</u>

BOD Load

Septage:	BOD = 1,500 mg/l	➔ 2,350 mg/l for the 1:9 mixture
Public toilet: sludge	BOD = 10,000 mg/l	

BOD_{load} = 140 m³/d x 2,350 mg/l = <u>329 kg BOD /d</u>

NH_3 toxicity

Septage: NH_4-N = 200 mg/l
Public toilet sludge: NH_4-N = 2,500 mg/l

The average concentration in the influent is thus:

0.9 x 200 mg/l + 0.1 x 2500 mg/l = 430 mg/l NH_4-N

NH_4-N losses in the sedimentation unit may amount to at least 5 %.

➔ NH_4-N influent to the pond system: 409 mg/l

By using Fig. 11 (Chpt. 5.6) which shows the relative amount of NH_4-N and NH_3-N as a function of pH and temperature, the expected NH_3-N concentration may be determined for $T_{avg.}$ = 25°C and assuming pH = 8:

5.38 % of NH_4-N ➔ NH_3-N = 22 mg/l

This concentration is below the threshold for NH_3 toxicity to anaerobic bacteria (see also Chpt 5.6). The facultative ponds will receive an even lower concentration due to ammonia loss in the anaerobic pond, which will amount to at least 5 %. NH_3-N concentrations will therefore not exceed 20 to 30 mg/l, and hence stay within the threshold limits for toxicity to algae.

For each specific ratio of public toilet sludge vs. septage, the above control calculation must, of course, be repeated.

The Sedimentation/Thickening Tanks

Similarly to septic tanks, settling/thickening tanks must ensure adequate liquid retention and sufficient storage space for scum and sludge accumulating during the desired desludging interval. The size of the settling/thickening tanks may be determined by assuming four distinct tank zones as shown in Fig. 13 below. The actual sludge density or TS (SS) concentration in these zones can be determined in an approximate manner through settling tests in 1-litre cylinders. However, cylinders with larger diameters to avoid boundary effects between the cylinder wall and the sludge mass are more suitable. Cylinder experiments may also be used to determine the SS concentration in the clear zone. Sludge concentrations attained in settling/thickening tanks in Accra/Ghana (Larmie 1994) may be used as a first approximation (Table 13).

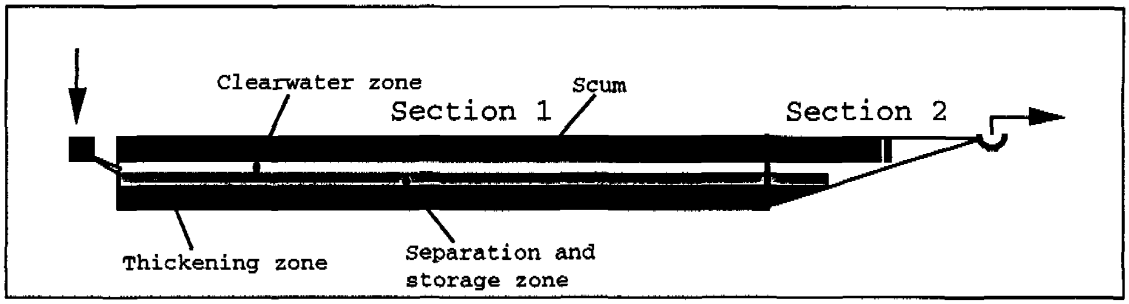


Fig. 13 Sedimentation/Thickening Tank with Four Distinct Layers of Separated Solids

Depending on the tank's length and on the slope of the ramp, the storage volume above the ramp (Sect. 2 in Fig. 13) amounts to 15-20 % of the volume of Sect. 1 of the tank. We recommend, however, to allocate only 10 % of the necessary storage volume to the ramp section to account for irregularities such as overloading, hydraulic short-circuiting and unexpected variations in sludge quality.

Table 13 Solids Concentrations Attained in Full-Scale Settling-Thickening Tanks in Accra, Ghana (Larmie 1994)

Zone	Depth from the surface (m)	SS concentration (kg/m^3)
Scum	0 - 0.8	160
Clear zone	0.8 - 1.3	4
Separation and storage zone	1.3 - 1.8	60
Thickening zone	> 1.8	140

The **required solids storage volume** and surface **area** in **Sect. 1** (accounting for 90 % of the required solids storage volume) is calculated as follows:

Assumptions:

Tank loading period: 30 days
SS elimination: 80 %

Sludge mass to be stored in Section 1 of the tank (90 %):

0.9 x30 days x 0.8 (TS elimination) x 3,000 kg SS = 64,800 kg

With a chosen effective tank depth of 3.20 m:

$$A_1 = \frac{64\,800 \text{ kg}}{0.8 \text{ m} \times 160 \text{ kg/m}^3 + 0.5 \text{ m} \times 60 \text{ kg/m}^3 + 1.40 \text{ m} \times 140 \text{ kg/m}^3}$$

(The denominator corresponds to the TS storable under 1 m^2 of tank surface; see also Table 13)

A_1 (surface area for Sect. 1) = 183 m^2

$$V_1 = \frac{64\,800 \text{ kg}}{354 \text{ kg/m}^2} \times 3.2 \text{ m} = \underline{586 \text{ m}^3}$$

Storage volume in Sect. 2 of the tank (10 %):

$V_2 = 0.1 \times 586 = 59 \text{ m}^3$

Total solids volume accumulating during 30 days of sludge delivery:

$V_{tot} = 586 + 59 = \underline{654 \text{ m}^3}$

Hence, the **specific solids storage volume V_s** (m^3 of separated solids per m^3 of FS delivered) on which to base the settling tank size may be calculated as follows:

$Q_{in} = 140 \text{ m}^3\text{/day}$ | x 30 days

$Q_{tot} = 4,200 \text{ m}^3$

$$\rightarrow \mathbf{Q_{solids} : Q_{tot} = V_s} = \frac{654}{4,200} = \mathbf{0.15 \text{ m}^3/\text{m}^3 \text{ FS}}$$

For FS mixtures exhibiting shares of public toilet sludge lower than the one used in the design example, this specific solids ratio constitutes a conservative estimate. Hence, a slightly lower ratio could be assumed. For mixtures with greater shares of public toilet sludge, a somewhat higher value of V_s must be used.

From a structural and operational viewpoint, and to achieve good hydraulic performance, the tank should be as long and as narrow as possible. ATV (1991) recommends a tank length of ≥ 30 m and a width of 4 to 10 m.

Given a width of 6 m, the length of the tank in Sect. 1 amounts to 30.5 m. The ramp (Sect. 2), which allows for front-end loader access, should have a maximum slope of 35 % (20°). The length of Sect. 2 will therefore amount to 9 metres.

The necessary liquid retention time can also be estimated from settling tests in 1-litre cylinders. Fig. 14 shows the results of such settling tests conducted with septage in Accra, Ghana, with 1-litre cylinders and with a cylinder of 20 cm diameter. Both types of tests indicate that the settling process is essentially complete after 120 minutes. A minimal nominal liquid retention time in the clearwater zone of four hours is suggested for safety reasons as actual retention times are always shorter than nominal ones due to hydraulic short-circuiting.

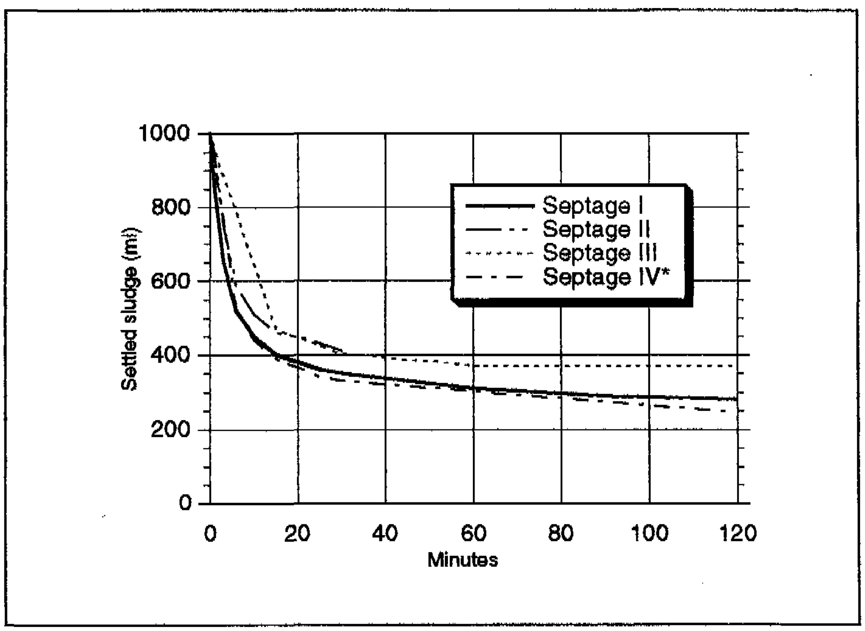


Fig. 14 Results of Settling Tests Performed in 1-Litre Cylinders (Septage I-III) and in a Cylinder of 20 cm Diameter and 2 m Height (Septage IV*)

Checking for the minimum liquid retention time in the clear zone:

Hourly influent: 140 m^3 / 8 hours = 17.5 m^3/h

Retention time:

183 m^2 x 0.5 m (clear zone) / 17.5 m^3/h = 5.2 hours (> 4 h)

This is the minimum liquid retention time at the end of the loading period when the tank has reached its solids accumulation capacity and the clear zone is at its shallowest.

Installing a stilling chamber into which the vacuum tankers discharge their load should ensure loading equalization.

In summary, the following unit tank size will result allowing for 30 days raw sludge loading and ensuring a nominal 5.2-hour liquid retention in the clear zone:

Sect. 1	Sect. 2 (ramp)
Length: 30.5 m Width: 6 m Depth: 3.2	Length: 9 m Slope: 35 % (20°)

Two tanks should be constructed to ensure alternate loading, consolidation and emptying of the batch-operated units.

The volume of accumulated solids to be stored during 30 days of tank loading was calculated as 654 m^3. The volume to be removed from the tank after an additional month of consolidation will, however, be less than this. It will amount to 550 - 600 m^3, only, as part of the solids attributed to the settling zone may be removed by the vacuum tanker along with the liquid contained in the clear water zone. Also, the separated solids will thicken further during the resting period. At a TS content of ≈ 14 %, in the order of 80 tons/month of solids removed from the settling tanks must be further treated (see Chpt. 4.6 regarding further solids treatment).

Solids accumulating in the first (anaerobic) pond must be removed yearly or bi-yearly. The respective sludge volume can be assumed to amount to 15 %, approximately, of the TS load, with a TS concentration of 14 %. Hence, in the order of 164 tons or 1,200 m^3 of settled solids will have to be removed yearly from the first pond. Together with the solids from the settling tanks, in the order of 1,000 tons or 7,000 m^3 per year of separated solids would have to be treated.

The area, which is required for further sludge treatment, is dependent on the chosen process and on the treatment objective (quality requirements). The sludge may be co-composted with sawdust or solid organic waste. The gross area thereby required would amount to approx. 1,500 m^2 (calculated as three times the net area required for windrows of 1.5 m of height). Alternatively, the sludge may be treated on sludge drying beds. Assuming a solids loading rate of 200 kg TS/m^2 y, an area of 5,500 m^2 of drying beds would be required to treat the solids from the settling tanks and from the primary pond.

Anaerobic Pond

Assuming a BOD elimination in the sedimentation tank of 40 %, the BOD load to the anaerobic pond amounts to:

$$0.6 \cdot 329 \text{ kg BOD/d} = 198 \text{ kg BOD/d}$$

With a chosen permissible volumetric loading of 300 $g/m^3 \cdot d$[1]:

$$V_{pond} = \frac{198{,}000 \text{ g BOD/d}}{300 \text{ g/m}^3 \cdot \text{d}} = \underline{660 \text{ m}^3}$$

Assuming a pond depth of 2.50 m to be available for anaerobic digestion, the pond area amounts to:

Pond area = $\underline{264 \text{ m}^2}$

Additional allowance of 0.5 m is made for the storage of solids separated of in the pond. Choosing a width to length ratio of 3: 1, the pond will have the following dimensions:

Length: 27 m
Width: 10 m

Starting with a BOD concentration in the raw FS of 2,350 mg/l, the effluent of the anaerobic pond is expected to exhibit the following BOD concentration:

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1 Based on the results of Uddin (1970), we believe that a higher BOD load could be applicable (Chpt. 5.3), however, we have not a sufficient amount of data at hand to prove this supposition.

BOD elimination in the sedimentation tank:	40 %
BOD elimination in the anaerobic pond:	70 %
Total BOD elimination:	82 %

➔ BOD in effluent = 423 mg/l

This BOD level is likely to constitute a lower limit of anaerobic degradation, based on monitoring results from Accra, Ghana. Also, this is a concentration, which allows an economical use of facultative ponds. Hence, in this example, one anaerobic pond will be sufficient.

Facultative Ponds

Assuming a BOD elimination in the anaerobic pond of 70 % (inclusive of a further BOD removal caused by sedimentation), the influent BOD load to the facultative pond, the surface area and geometry are calculated as follows:

BOD load = 0.30 x 198 kg BOD/d = 59.5 kg BOD/d

With a chosen permissible BOD loading rate of 350 kg/ha·d at 25 °C (Mara 1992):

$$A_{pond} = \frac{59.5 \text{ kg BOD}}{350 \text{ kg/ha·d}} = 0.17 \text{ ha} = \underline{1{,}700 \text{ m}^2}$$

Two ponds of 850 m^2 each shall be constructed, using a depth of 1.50 m. With a length to width ratio of 7 : 1, pond dimensions of 11 m x 77 m will result.

The final effluent quality can be estimated as follows:

BOD_{final} = [(0.6 (sed.tank) x 0.3 (anaerobic pond) x 0.2 (facultative pond)] x 2,350 mg/l

= 85 mg/l (unfiltered sample)

Assuming that 50–70 % of this constitutes suspended algal cells, the BOD in a filtered sample would amount to 25–40 mg/l, and thus represent an excellent effluent quality. If further treatment is necessary, e.g. to satisfy faecal coliform (FC) quality standards for effluent reuse in agriculture, the final effluent may be treated in maturation ponds. These could be designed following the design rules for wastewater maturation ponds (see e.g. Mara 1992). Each pond upstream of the first maturation pond may be assumed to bring about a FC reduction of a factor of 10, i.e. one order of magnitude or log cycle. In our design example for tropical climate (T • 25 °C), two maturation ponds each with a retention time from 3 - 5 days will suffice to ensure final FC concentrations of 10^3 to 10^2 counts/100 ml.

The effluent flow rate will be smaller than the raw FS delivery rate by the volume of the solids separated in the sedimentation unit (5-8 % of the raw FS flow) and by the net evaporation from the facultative pond. Evaporative losses in anaerobic ponds are expected to be minor, as the ponds are likely to be partly or fully covered with scum. Hardly any evaporation will occur in the sedimentation units, which always carry a thick scum layer.

Assuming an average daily net evaporation of 1mm, the effluent flow from the facultative ponds will amount to:

$$Q_{final} = 0.93 \text{ (sed.tank)} \times 140 \text{ m}^3 - (19 \text{ days}_{facult.\ pond} \times 0.001 \text{ m} \times 1{,}700 \text{ m}^2)$$

$$= \underline{98 \text{ m}^3/\text{d}}$$

By adding two maturation ponds with an additional retention time of 4 days each the final effluent amounts to:

$$Q_{final} = 98 \text{ m}^3/\text{d} - (8 \text{ days} \times 0.001 \text{ m} \times 571 \text{ m}^2)$$

$$= \underline{93 \text{ m}^3/\text{d}}$$

Land Requirements

Land requirements in absolute terms as well as indicated on a per-capita and per unit BOD load basis are shown in Table 14 below. The Table first lists the area required for basic treatment. Additional land will be required to treat the sludge solids removed from the settling tanks and from the primary pond. Land needed for liquid polishing in maturation ponds may also have to be considered.

Table 14 Land Area Required for FS Treatment (based on the design example)

Treatment unit	Area required [m²]	Area required per capita [m² / cap]	Area required per unit load of BOD in the untreated FS [m² / kg BOD_{in}]
Basic treatment (net area):			
• Settling/thickening	474		
• Anaerobic pond	264		
• Facultative pond	1,700		
Total net area for basic treatment:	2,438	0.018	7.4
Polishing treatment (net area):			
• Maturation ponds (2)	571		1.7
Total net area	3,009		9.1
Gross area for basic + polishing treatment (= net area x 1.3):	3,912		11.8
Treatment for separated solids (gross area):			
• Co-composting	1,500		
• Drying beds	5,500		
Gross overall area:			
• With solids treated by co-composting	**5,400**	**0.04**	
• With solids treated on drying beds	**9,400**	**0.07**	

It should be noted that the land requirement of **7.4 m²/kg BOD** is considerably less than the figure of 13 m²/kg BOD listed in Table 9. Figures in Table 9 were calculated for the treatment of septage without the co-mixing of public toilet sludge whereas a mixture of septage and public toilet sludge has been used in the above design example. Organic constituents in the fresh public sludge are well digestible. Therefore, the BOD elimination rate in anaerobic ponds treating a mixture of septage and public toilet sludge is higher (70-80 %) than in anaerobic ponds treating septage only (40 %). As a consequence, a smaller surface area will result.

The net treatment area as calculated above should be enlarged by about 30 % to allow for embankments and access roads. This would result, in our example, in a gross area for the settling tanks, anaerobic and facultative ponds of 10 m^2/kg of influent BOD, approximately. This is, quite expectedly, in accord with 10 m^2/kg of influent BOD as calculated from the area requirement of 0.5 m^2/cap (Mara 1997) for a WSP system comprising an anaerobic and a facultative pond and using 45 g BOD/cap·day.

The **per-capita** land requirement are much lower than the 0.5 m^2/cap of net pond area calculated by Mara (1997) for a WSP system treating wastewater in tropical climate (T = 25 °C) and comprising anaerobic and facultative ponds. This is due to the fact that most of the BOD reaching the pits and vaults of on-site sanitation systems is "lost" or reduced prior to the collection by vacuum tankers. Some of it leaves the tank via the liquid effluent infiltrating into the soil. The other part is reduced through anaerobic degradation of the faecal material retained in the system. The BOD contribution in collected septage in the tropics, e.g., amounts to approx. 1 g/cap·d only (as against 45 g/cap·d in fresh excreta; see also Table 5).