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Low-Cost Options for Pathogen Reduction and Nutrient Recovery from Faecal Sludge

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Abstract

Recently, the application of excreta-based fertilizers has attracted attention due to the strongly increasing prices of chemically produced fertilizers. Faecal sludge from on-site sanitation systems is rich in nutrients and organic matter, constituents which contribute to replenishing the humus layer and soil nutrient reservoir and to improving soil structure and water-holding capacity. Hence, it represents an important resource for enhancing soil productivity on a sustainable basis. However, there is little in the scientific literature about the performance of treatment technology allowing recovery of nutrient resources from human waste. This paper reviews the state of knowledge of different processes that have been applied worldwide. Their pathogen removal efficiency as well as nutrient and biosolids recovery performances are assessed. The chapter outlines the gaps in research for further development.

Introduction

Contrary to wastewater management, the development of strategies and treatment options adapted to the conditions prevailing in developing countries to cope with faecal sludges (FS), the by-products of on-site sanitation installations, have long been neglected. In recent years though, an encouraging number of initiatives for improved FS management, including the devising of appropriate FS treatment schemes, have emerged, for instance in several West African countries (Senegal, Mali, Ivory Coast, Burkina Faso, Ghana) and in Southeast Asia (Nepal, Philippines, Thailand, Vietnam) as well as in Latin America. These initiatives help urban dwellers and authorities to overcome the challenges posed by what might be designated the 'urban shit drama' – the indiscriminate and uncontrolled disposal of faecal sludges into drains, canals and open spaces, thereby creating a 'faecal film' prevailing in urban areas and impairing public health, causing pollution, and creating nose- and eyesores.

The authors estimate that in the order of one-third of the world population (approximately 2.4 billion urban dwellers) rely on on-site sanitation installations, namely unsewered family and public latrines and toilets, aqua privies and septic tanks. This situation is likely to last for decades to come, since city-wide sewered sanitation is neither affordable nor feasible for the majority of urban areas in developing countries. Using the figure of 1 litre FS/cap/day as an average FS generation rate in urban areas (based on literature data and our own investigations), in a city of 1 million inhabitants, in the order of $1000m^3/d$ of FS should be collected and disposed of daily. However, reported daily collection rates for cities much larger than this (e.g. Accra, Bangkok and Hanoi) rarely exceed $300–500m^3/d$. This indicates that huge quantities, if not the major fractions, of the FS generated are disposed of unrecorded or clandestinely within the urban settlement area.

When full, latrines are emptied mechanically by emptying trucks, or manually by labourers or family members (sometime the only option for the poorest households). While mechanically emptied sludge, from planned and accessible areas, can be transported and disposed of several kilometres from people's homes, the manually emptied sludge from inaccessible low-income areas is usually deposited within the family's compound, into nearby lanes, in nearby drains or on open land. These practices, often unrecorded, represent a significant risk to public health and have a high disease impact on emptying operators, their families, the households living in the immediate area and on vulnerable populations in latrine-based cities. To achieve effective and sustained health protection for these exposed urban populations, future latrine provision programmes must develop an approach that links on-site sanitation infrastructure to the transport system and safe reuse or disposal/treatment of the emptied faecal sludge (solids, liquid, or a mixture of both). This approach could be different for the planned and densely populated slum areas.

The low-cost FS treatment processes considered by the authors to be potentially suitable for developing countries comprise mainly non-mechanized options as listed below. These options are not sufficiently documented and updated in the existing literature.

Faecal sludge low-cost treatment options considered in this chapter

- settling/thickening tanks or ponds (non-mechanized, batch-operated);
- unplanted drying beds;
- constructed wetlands;
- combined composting ('co-composting') with organic solid waste;
- pond treatment of FS supernatants or percolates;
- land application in hot arid to semi-arid regions;
- anaerobic digestion with biogas utilization;
- lime stabilization.

These options, with the exception of anaerobic digestion and lime stabilization, have been experimented upon and investigated during ten years of collaborative field research with selected partners in Latin America, West Africa and Asia. Information on mechanized and energy-intensive sludge processing systems currently used in industrialized countries is described in International Solid Wastes and Public Cleansing Association Working Group on Sewage and Waterworks Sludge (1998).

CHALLENGES IN TREATING FAECAL SLUDGES

The choice of a FS treatment option depends primarily on the characteristics of the sludges generated in a particular town or city and on the treatment objectives (agricultural reuse, landfilling of biosolids, or discharge of treated liquids into receiving water bodies). Like for wastewater, FS characteristics vary widely within and between cities, based on the types of on-site sanitation installations in use (e. g. dilution factor) and whether manual or mechanical emptying practices are used. Sludges from septic tanks are biochemically more stable due to the long storage periods compared to sludges from installations which are emptied weekly (e.g. public toilet vaults). In cities like Bangkok, Hanoi and Buenos Aires, for instance, septic tanks are the predominant form of on-site sanitation installations. When septic tanks are emptied, both the solid and liquid portions are usually pumped out. Where soak pits are used for infiltrating the septic tank supernatants, they may have to be emptied, too, due to clogging. This contributes to diluting the FS collected in a particular settlement. In West Africa, an important fraction of the urban population relies on public toilets, which are usually highly frequented. In Kumasi (Ghana), a city of 1 million inhabitants, 40 per cent of the population rely on unsewered public toilets, which are emptied at weekly intervals. The sludges collected from these installations are biochemically unstable (high in BOD_5) and exhibit high ammonium (NH_4^+-N) concentrations, as urine is disposed of with the faeces.

The specific challenges in treating FS in developing countries, as opposed to treating wastewater, lie in the fact that pathogen concentrations are higher by a factor of 10 to 100 in FS than municipal wastewater and that appropriate, affordable and enforceable discharge and reuse standards or guidelines pertaining to FS treatment are lacking. Table 9.1 lists FS characteristics observed by the authors and their partners in selected cities in Africa and Asia. The fact that FS exhibit widely varying characteristics calls for a careful selection of appropriate treatment options, especially for primary treatment. This may encompass solids–liquid separation or biochemical stabilization if the FS is still fresh and has undergone only partial degradation during on-plot storage and prior to collection. Faecal and wastewater treatment plant (WWTP) sludges may, in principle, be treated by the same type of modest-cost treatment options.

Why recycle human excreta?

Faecal sludges are rich in nutrients and organic matter – constituents which contribute to replenishing the humus layer and soil nutrient reservoir and to

Table 9.1 *Faecal Sludge (FS) characteristics in selected cities in developing countries*

Parameters	Accra (Ghana)	Accra (Ghana)	Yaoundé (Cameroon)	Bangkok (Thailand)	Alcorta (Argentina)
Type of FS	Public-toilet sludge[a]	Septage[b]	Septage	Septage mean (range)	Septage mean (range)
TS (mg/l)	52,500	12,000	37,000	15,350 (2200–67,200)	(6000–35,000) (SS)
TVS (% of TS)	68	59	65	73	50 (VSS)
COD (mg/l)	49,000	7800	31,000	15,700 (1200–76,000)	4200
BOD_5 (mg/l)	7,600	840	N/A	2300 (600–5,500)	(750–2600)
TN (mg/l)	N/A	N/A	1100	1100 (300–5,000)	190
NH_4-N (mg/l)	3300	330	600	415 (120–1,200)	150
Ascaris (Eggs number/gTS)	N/A	(13–94)	2813	(0–14)	(0.1–16)

TS: total solids; SS: suspended solids; TVS: total volatile solids; VSS: volatile suspended solids; COD: chemical oxygen demand; BOD_5: biochemical oxygen demand; TN: total nitrogen.

[a]Sludge collected from latrines shared by a high-density population or latrines with very high emptying frequency (weeks, months).

[b]Sludge collected from septic tanks after two to five years. Septage is well digested and less concentrated in solids and nitrogen than public-toilet sludge.

Source: Based on investigations conducted by SANDEC's field research partners improving soil structure and water-holding capacity. Hence, they represent an important resource for enhancing soil productivity on a sustainable basis. Unfortunately, in most urban areas of developing countries, FS management remains largely unregulated and chaotic, hence it causes contamination of soils and water bodies and endangers human health.

Many municipal decision-makers are well aware, though, that developing and applying sound recycling strategies would greatly contribute to alleviating the management problems. However, little action has been taken to recycle FS on a sustainable basis. It has been estimated that, worldwide, the global fertilizer industry produces some 170 million tons of fertilizer nutrients annually (International Fertilizer Industry Association, 2009), while at the same time 50 million tons of fertilizer equivalents are dumped into water bodies via sewered sanitation systems (Werner, 2007). Recovery of organic matter and nutrients from human waste as biosolids is an economic necessity and an urgently needed environmental protection strategy. As a consequence, strategies and low-cost technological options for excreta treatment have to be developed which allow the cost-effective and affordable recycling of organic matter and nutrients especially to urban and peri-urban agriculture.

Drangert (1998) reported the fertilization equivalent of human excreta, which is, in theory at least, nearly sufficient for a person to grow his own food. However, the value of nutrients that can be recovered during recycling would be less than that contained in the raw excreta since it is impossible to recover all the value in whatever treatment option is adopted. The nutrient content in FS shows that it is a potential resource which should be utilized by farmers to replenish soil fertility for increased crop yield. It could be mixed with organic solid waste to generate very good fertilizer material. The organic waste fraction in solid waste remains the largest proportion that can be recovered. The high content of organic matter (50–90 per cent) provides an opportunity for exploitation through composting processes (Allison et al., 1998; Asomani-Boateng and Haight, 1999).

Nutrient recovery and biosolids sanitizing processes

The separating of the solids and liquids which make up FS is the process-of-choice in FS treatment, unless it is decided to co-treat FS in an existing or planned wastewater treatment plant or if the FS loads are small compared to the flow of wastewater. Solids–liquid separation may be achieved through sedimentation and thickening in ponds or tanks or filtration, and drying in sludge drying beds. Table 9.2 provides an overview of how selected treatment processes or process combinations are able to achieve reductions of certain contaminants or constituents. The separated solids will in most cases require further storage, dewatering, drying or composting, resulting in biosolids usable as a soil conditioner-cum-fertilizer. Upon separation, the liquid fraction can be used directly for agriculture or other

Table 9.2 *Overview of selected options and expected removal (recovery) efficiencies in faecal sludge solid–liquid separation treatment systems*

Solids–liquid separation options	Design criteria	Treatment goal / achievable removal		
		Solids–liquid separation	Organic pollutants in liquid fraction, after separation	Parasites (helminth eggs)
Settling/ thickening tank	SAR[a]: 0.13m^3/ m^3 of raw FS HRT: ≥ 4 h S: 0.006 m^2/cap (Accra)	SS: 60–70% COD: 30–50%	To be processed for further improvement in ponds or constructed wetlands	Concentrated in the settled and floating solids
Settling/ anaerobic pond	300–600g $BOD_5/m^3/d$ HRT: ≥ 15 days SAR: 0.02m^3/m^3 (Rosario) and 0.13m^3/m^3 (Accra)	BOD_5 > 60–70%	Filtered BOD_5 > 50%	Concentrated in the settled and floating solids
Unplanted drying/ dewatering beds	100–200kgTS/ m^2/year S: 0.05 m^2/cap (Accra)	SS: 60–80% COD: 70–90% NH_4^+-N: 40–60%	To be treated for further improvement in ponds or constructed wetlands	100% retained on top of the filtering media
Planted drying beds (humification beds)	≤ 250kgTS/m^2/ year SAR: 20cm/year (Bangkok)	SS > 80% SAR: 20cm/year	To be treated for further improvement in ponds or constructed wetlands	100% retained on top of the filtering media
Co-composting with solids waste	Mixing ratio FS/ SW = 1/2–1/3	N/A	N/A	1–2 log units
Facultative stabilization ponds	350kg BOD_5/ ha/d	Not for this purpose	> 60% removal of total BOD_5	Removed by settlement

[a]Solids Accumulation Rate = the amount of solids that accumulate in a treatment system until the operation is stopped.
S: surface area required per capita, HRT: hydraulic retention time
Source: Kone and Strauss (2004)

purposes such as aquaculture. In areas where reuse is not an option, it will undergo a polishing treatment to satisfy criteria for discharge into surface waters and/or to avoid groundwater pollution, where effluents are allowed to infiltrate.

Biosolids recovery through faecal sludge solids–liquid separation

The choice of either sedimentation tanks or ponds, besides depending on the type of sludges to be treated, is also determined by the mode of operation envisaged and by the provisions which are made for handling the mass of solids to be periodically removed from these primary treatment units. Solids quantities produced in sedimentation/thickening tanks, which, in their low-cost version, will be non-mechanized and batch-operated in loading/consolidating cycles of weeks to a few months, will be much smaller than the mass of solids to be emptied and handled from primary ponds. These have typical operating cycles of 6–12 months, unless measures are introduced, by which settled solids are evacuated at higher frequencies without stopping pond operations.

Settling ponds

Suspended solids (SS) retention efficiencies of up to 96 per cent are achieved in two alternating, batch-operated septage sedimentation ponds in Alcorta, Argentina (Ingallinella et al., 2002). The concomitant solids accumulation rate amounts to $0.02m^3/m^3$ of raw FS. The quality of the septage pond effluent (COD = 650mg/litre, BOD_5 = 150mg/litre, NH_4^+-N = 104mg/litre) resembles that of urban wastewater, allowing the combined treatment of the two liquids in a waste stablization pond (WSP) system comprising a facultative and a maturation pond (Ingallinella et al., 2002). Septage deliveries to the pond in operation are suspended and the supernatant transferred to the parallel pond when the settled solids layer has reached 50cm. The accumulated sludge is left to dewater until a total solids (TS) concentration of >20–25 per cent is achieved, allowing it to be shovelled. This lasts up to six months under the temperate-subtropical climate prevailing in the particular area (400km west of Buenos Aires). Bulking material such as grain husks, sawdust or woodchips could be used under such conditions to shorten the in situ storage and dewatering time. This type of settling pond design is based on an assumed pond-emptying frequency and on the known or expected solids accumulation rate.

Settling/thickening tanks

Twin, batch-operated, non-mechanized sedimentation/thickening tanks were put into use by the Accra (Ghana) Waste Management Department in 1989 to treat septage and public-toilet sludges at mixing ratios of approximately 3:1. The tanks were intensively investigated by the Ghana Water Research Institute and SANDEC from 1994–1997 (Heinss et al., 1998). Four distinct zones were observed to develop while FS loading was in progress: a lower bottom thickening zone with TS up to 140g/litre (14 per cent), an upper bottom zone with 60gTS/litre, a settled water zone with 3–4gTS/litre and a scum layer containing up to 200gTS/litre. The settled solids accumulation rate was $0.16m^3/m^3$ of raw FS and SS retention ranged from 60–70 per cent. The average COD and SS contents in the tank effluents amounted to 3000mg/litre and 1000mg/litre, respectively.

Unplanted drying/dewatering beds

Unplanted drying beds can be used for dewatering and drying of septage, septage/public-toilet sludge mixtures (at volumetric ratios > 2:1) and of primary pond sludges with initial TS content varying from 1.5 to more than 7 per cent. Dewatering performance varies with the initial TS and TVS (total volatile solids) content and the applied loads. Pescod (1971), in conducting septage dewatering/drying experiments on yard-scale drying beds in Thailand, found that 5–15 days of dewatering were necessary to reach a TS content of 25 per cent with initial solids loading rates varying from 70 to 475kgTS/m^2/year and a loading depth of 20cm. In Ghana, a dewatered sludge with 40 per cent TS was obtained from a mixture of septage/public-toilet sludge in 12 days, with an initial solids loading rate of 200kgTS/m^2/year and a loading depth of < 20cm. With a solids loading rate of 130 TS/m^2/year, a sludge with 70 per cent TS was obtained in nine days and a reduction in the percolating liquid (compared to the raw sludge mixture) of 60 per cent BOD_5 and 70 per cent COD was achieved (Heinss et al., 1998).

Planted dewatering/drying beds (constructed wetlands)

Constructed wetlands have been successfully operated by the Asian Institute of Technology (AIT) from 1997–2004, for treating septage in Bangkok, containing 14,000–18,000mgTS/litre. An optimum loading rate of 250kgTS/m^2 per year was established, based on seven years of field research with three pilot constructed wetland beds (Koottatep et al., 2005). The beds were planted with *Typha angustifolia* (narrow-leaved cattail). Each bed had a surface of 25m^2 and was fed with 8m^3 of septage once a week. Impounding of the percolate proved necessary to secure sufficient humidity for the cattails, which developed wilting symptoms during dry seasons. Overall, 70–80 per cent TS, 96–99 per cent SS and 95–98 per cent total COD (TCOD) removals were achieved in the liquid fraction of the septage. TCOD removal was improved by impounding and so was nitrogen removal through denitrification. Ponding periods of six days were found to be optimal. The constructed wetlands were able to accumulate 70cm of sludge after four years of operation while maintaining their full permeability. The TS content of the dewatered sludge varied from 20–25 per cent in the uppermost layer (< 20cm) to 25–30 per cent in the deeper layers. Under steady loading conditions, the percolate quality was constant. TCOD in the percolate amounted to 250–500mg/litre, TS to 1500–4000mg/litre and SS to 100–300mg/litre. Experiments with biochemically unstable and highly concentrated sludges like those from public toilets in West African cities have not been conducted to date.

Nitrogen recovery

Settling tanks and ponds

Nitrogen lost in settling tanks (Table 9.2) is negligible due to the absence of nitrification under the fully anaerobic conditions prevalent. In pond schemes, nitrogen is stored in the organic form by newly forming biomass that later settles and accumulates in the sediments. Additional losses may occur by ammonia (NH_3) volatilization if overall hydraulic retention times are sufficiently long (weeks to months) and pH rises above 8, enabling the formation of NH_3 in the pH-dependant NH_4/NH_3 equilibrium (Heinss et al., 1998).

Unplanted drying beds

Organic nitrogen is filtered with the suspended solids retained on the bed surface (90–97 per cent). NH_3-N is lost by volatilization depending on local climatic conditions (wind, temperature, rain). Experiments from Ghana, conducted with different types of sludges, resulted in nitrogen recovery of 35–70 per cent (Cofie et al., 2006).

Planted dewatering/drying beds (constructed wetlands)

Nitrogen recovery of 55–60 per cent in planted dewatering beds treating septage is estimated to be due mainly to the accumulation of organic nitrogen in the dewatered sludge layers. Losses of nitrogen are due to NH_3 volatilization and nitrification/denitrification processes, and account for 15–35 per cent (Panuvatvanich et al., 2009). Percolate concentrations of 100–200mg/litre of organic and ammonia nitrogen and 50–150mg/litre of NH_4^+-N were observed at AIT's pilot scheme with initial concentrations of 1000 and 350mg/litre N, respectively (Koottatep et al., 2005).

Co-composting

The dynamics of nitrogen during co-composting of FS and organic solid waste have been documented (Cofie et al., 2006, 2009). Researchers found that the highest concentrations of ammonia-nitrogen recovered from co-composting of FS with organic solid waste occurred during the early stages of composting, when the organic matter degradation is most intense and NH_4-N is produced through the mineralization of organic nitrogen. NH_4-N concentration decreased continually during the thermophilic phase up to day 40 and then remained fairly stable afterwards until the end of maturation. It was observed that after 50 days of composting no further significant degradation of NH_4-N could be observed as the compost is maturing with a final value of 0.01 per cent of ammonium nitrogen.

For nitrate (NO_3-N), little nitrification can be observed under the thermophilic conditions. After the thermophilic phase, when the inner temperature is around 45°C, nitrification begins and a drastic decrease in ammonium concentration occurs. This started to occur after 30 days of composting. The nitrate value of 0.04 per cent at this point rose steadily and reached its maximum value of about 0.12 per cent after 60–70 days of composting.

Both organic nitrogen and total nitrogen (TN) have similar behaviour during co-composting of dewatered FS with organic solids waste. During the thermophilic phase, the nitrogen concentration remained fairly constant. During maturation the nitrogen levels rose higher than during the thermophilic phase. The final organic nitrogen value was about 1.05 per cent TS and the TN value was about 1.16 per cent TS.

Faecal sludge liquid fraction

Although high losses of nitrogen can occur in some of the above treatment processes, the effluent (or percolate) still contains high concentrations of nitrogen which can be used for irrigation. Where the possibility of recycling into agriculture exists, the salt content is often a limiting factor. Electrical conductivities (EC) observed in the supernatants of the Accra sedimentation tanks ranged from 8–10mS/cm but salt tolerance limits of even the most tolerable plants are 3mS/cm. Percolates from the AIT's planted dewatering units exhibited EC values of 2–5mS/cm. However, the long-term impact on soil salinity may be negligible as the high conductivity in the percolates or supernatants is mainly due to the high concentration of NH_4^+.

In Ghana, pond systems have been developed to polish effluent from the settling/thickening tank pre-treatment units. Algal growth was inhibited due to the excessive ammonia content caused by the highly concentrated public-toilet sludges. These exhibit NH_4^+-N + NH_3-N levels of > 3000mg/litre leading to NH_3-N levels in the FS liquids which are beyond the toxicity limits of algae (40–50mg NH_3-N/litre). In Kumasi, where septage and public-toilet sludges are collected and disposed in ponds at a volumetric ratio of 1:1, NH_3 volatilizing from the FS pond scheme causes eye irritation during periods of high temperature and during periods of insufficient winds. Ammonium concentrations in the public-toilet sludges, coupled with high ambient temperatures of >28°C, favour the release of obnoxious amounts of NH_3-N (Strauss et al., 1997).

Pathogen inactivation (biosolids sanitization)

The fate of pathogens during FS solid–liquid separation processes depends on their size and degree of particle association. Due to their large size, helminth eggs are concentrated with the solids, whereas bacteria and viruses may be found both in the liquid and attached to particles in the solids. Under most conditions, helminth eggs are expected to be the most resistant pathogens in FS. Although die-off of helminth eggs in the sludge layer of ponds has been documented (Nelson et al., 2004; Sanguinetti et al., 2005), some eggs can survive for many years. Low-cost treatment options such as planted drying beds, unplanted drying beds or co-composting can achieve high inactivation efficiency of helminths eggs when treating faecal sludge (Table 9.3).

Percolates from planted and unplanted drying beds are free of helminth eggs as they are filtered with the solids by the sand layer. In Cameroon, Kengne et al.

(2009) showed that the planted drying beds can reduce helminth egg concentration from 78.9 eggs/gTS to 4.0 eggs/gTS after a six-month loading period follow by six additional months' resting. No *Ancylostoma duodenale*, *Strongyloides stercoralis*, *Enterobius vermicularis* and *Taenia* sp. eggs were present after a four-month resting period for the sludge. During the six-month resting period, the biosolids dry-matter content increased from 51 to 77 per cent. However, the biosolids were not entirely sanitized after this storage period as regards compliance with the WHO Guidelines of less than one egg/gTS for safe agricultural practice (WHO, 2006). Hence prior to direct application on fields, further storage for at least one month protected from rain or other additional treatment may be necessary. Similar results were also obtained by Sanguinetti et al. (2005), who found a significant reduction of *Ascaris* egg viability with decreasing humidity (below 40 per cent) in unplanted drying beds in Argentina. From the authors' experience, a minimum six-month storage time is required to sanitize faecal sludge in planted dewatering beds under tropical conditions; the rate of sanitizing depends on the degree of drying.

Co-composting has been tested successfully as a means to sanitize faecal sludge due to the high temperatures produced during aerobic composting. In dewatered FS co-composted with municipal solid waste, greater than a 1 log unit removal of helminth eggs was achieved after two months (Koné et al., 2007). During the first month, the temperature at the centre of the compost pile was higher than 60°C, and near the edge it was initially above 45°C. These temperatures may increase the permeability of the *Ascaris* eggs' shell (Barrett, 1976), allowing transport of harmful compounds, as well as increasing the desiccation rate of the eggs (Capizzi-Banas et al., 2004; Feachem et al., 1983; Gaspard and Schwartzbrod, 2003). The decrease in moisture content in the eggs may reduce the helminth larvae's mobility and movement, thus contributing to their decay (Sanguinetti et al., 2005; Stromberg, 1997; Wharton, 1979).

Table 9.3 *Pathogen inactivation efficiency of selected low-cost faecal treatment options*

Treatment option or process	Helminth egg log reduction	Duration (months)	References
Settling ponds	3	4	Fernandez et al. (2004)
Planted dewateringdrying beds (constructed wetlands)	1.5	12	Koottatep et al. (2005)
Unplanted drying/dewatering beds (for pre-treatment)	0.5	0.3–0.6	Heinss et al. (1998)
Composting (windrow, thermophilic)	1.5–2.0	3	Koné et al. (2007)
pH elevation > 9	3	6	Chien et al. (2001)
Anaerobic (mesophilic)	0.5	0.5–1.0	Feachem et al. (1983); Gantzer et al. (2001)

Source: Adapted from WHO (2006)

Thus, the combination of unplanted drying beds and co-composting of subsequently dewatered sludge can produce hygienic biosolids safe for agricultural reuse. Additional options for treatment include maintaining high pH (Capizzi-Banas et al., 2004; Gaspard and Schwartzbrod, 2003), particularly in the presence of ammonia (Pecson et al., 2007; Pecson and Nelson, 2005). High pH can be achieved by addition of lime or ash; if quicklime (CaO) is used, heat is also generated. Because of the high NH_4^+-N content of FS (Table 9.3), rapid inactivation of *Ascaris* eggs by the neutral form of NH_4^+-N can occur. However, this process will also lead to rapid loss of NH_4^+-N due to volatilization, which is undesirable for nitrogen recovery. Also, this process has not yet been tested in the field for FS treatment.

Based on epidemiological and the quantitative microbial risk assessment (QMRA), Navarro et al. (2009) showed that higher helminth egg concentrations in biosolids did not significantly increase consumers' and farmers' health-risk exposure. Indeed, the current WHO Guidelines (WHO, 2006) were not developed using epidemiological evidence on this aspect. As a consequence, the indicative guideline value of 1 helminth egg/gTS in biosolids appears to be more stringent than necessary and unaffordable to achieve in most cases in developing countries.

Biosolids heavy metal content

Biosolids generated from constructed wetlands can be recycled in agriculture without reservation as regards heavy metal content, as tests in Bangkok exhibited relatively low trace element concentrations (mg/kgTS) of 63 Pb; 14 Ni; 26 Cr;

Table 9.4 *Trace elements in biosolids recovered from constructed wetlands*

Parameters	Trace elements concentration (mg/kgTS)				
	Biosolids (Kengne et al., 2009)	Co-compost MSW/FS: 3:1 (Cofie et al., 2008)	Co-compost MSW/FS: 2:1 (Cofie et al., 2008)	Limit values in EC eco label compost (Hogg et al., 2002)	Limit values in Spain sewage sludge (Hogg et al., 2002)
Fe	9579 ± 14	–	–	–	–
Pb	63 ± 32	24 ± 13	34 ± 41	100	750
Ni	14 ± 3	12 ± 2	9 ± 2	50	300
Cr	26 ± 4	90 ± 32	62 ± 20	100	1000
Cd	2.4 ± 0.8	0.4 ± 0.1	0.0 ± 0.2	1	20
Cu	575 ± 283	–	–	100	1000
Zn	703 ± 436	–	–	50	2500
Mn	186 ± 25	–	–	–	–
Se	32 ± 16	–	–	–	–
Si	2779 ± 551	–	–	–	–

24 Cd; 575 Cu; 703 Zn; 186 Mn and 32 Se (Table 9.4). These values are below the limits acceptable for sewage sludge application or disposal in most European countries (Hogg et al., 2002). Concentrations of Pb, Ni and Cr are even below the limiting values of the European Communities eco label composts. These results showed that FS emptied mechanically in Bangkok is not highly contaminated by heavy metals. However, this may be a concern in areas where industrial sludges are mixed with FS for disposal.

In addition to this, co-composting of FS with organic solid-waste-generated compost with an acceptable content of heavy metals was found to be less than even the strict Swiss standard for compost (ASCP, 2001), except for Mercury (Hg), which in principle may still be acceptable following other European standards as summarized by Brinton (2001). Hence co-composting does not pose any environmental problems regarding heavy metal accumulation on agricultural land. It was observed that the Ni and Cr concentrations in the 3:1 (solid waste: FS) mixing ratio are significantly higher than in the 2:1 mixture. This observation implies that heavy metals are introduced to compost by the organic solid waste rather than FS. Therefore, the use of FS as a nitrogen source does not introduce high levels of heavy metals into the finished compost.

CONCLUSIONS

Human excreta collected as FS from on-site sanitation systems in developing countries can be converted into safe biosolids or pathogen-free liquid for reuse in agriculture. Although pathogen concentrations, particularly helminth eggs, are high in FS, filtration systems such as drying beds (planted and unplanted) concentrate them into the solids fraction, hence delivering a liquid phase free of helminths.

Comparing planted and unplanted drying beds, the concentration of pathogens in the sludge accumulated from the planted drying beds is reduced because of the reduction in moisture content. Other factors such as lack of nutrients also play an important role in pathogen decay. However, sludge accumulated by unplanted drying beds may still contain helminth eggs if the drying time is not long enough. Hence, these sludges need to be further treated, i.e. by co-composting before safe reuse in agriculture.

Thermophylic co-composting with organic solid waste produces safe biosolids as helminth eggs are inactivated mainly during the heating phase. Because of its high nitrogen content, dewatered faecal sludge constitutes a good complementary substrate to organic solid waste, which is rich in carbon.

The biosolids produced from these processes are rich in nutrients and safe, from the perspective of heavy metal concentrations, when compared to existing guidelines for biosolids reuse in agriculture. Considering the current food crisis, the potential for reusing by-products of FS processing systems will provide a tangible mitigation strategy to enhance agricultural soil productivity and farmers' incomes, as this product is available at competitive prices compared to industrial fertilizer.

Gaps in research

The world sanitation community has recently defined sustainable sanitation as systems which take into consideration all aspects of sustainability. They should protect and promote human health by providing a clean environment and breaking the cycle of disease. In order to be sustainable a sanitation system has to be not only economically viable, socially acceptable, and technically and institutionally appropriate, it should also protect the environment and the natural resources. Hence, when improving an existing sanitation system and/or designing a new one, it is suggested that the following sustainability criteria be considered: health aspects, environment and natural resources; technology and operation; financial and economic issues; and socio-cultural and institutional aspects (Sustainable Sanitation Alliance, SuSanA, 2008). This opens interesting prospects for FS-based products as organic fertilizer in agricultural applications in developing countries. Indeed, a range of pollutants can occur in FS, including pharmaceutical compounds, natural and artificial hormones, and pathogens. In view of the fact that the application of pharmaceuticals in developing and transition countries is increasing, the application of untreated FS on a large scale could lead to unforeseeable environmental risks (Lienert et al., 2007). Therefore, in addition to sanitizing FS, the removal of micropollutants and their derivatives is considered to be a key factor contributing to sustainability if FS is to be applied for reuse in agriculture (Shannon et al., 2008; UNEP, 2002).

When developing new treatment options in developing countries, the availability of sufficient and reliable energy often dictates the choice of the technology or sanitation systems. Energy consumption during the operation of a particular sanitation system is also a key aspect concerning its environmental and economic sustainability (van Timmeren and Sidler, 2007). It is estimated that 75 per cent of sub-Saharan Africans (550 million people) and some 50 per cent of South Asians (700 million people) do not have access to electricity. Given the problems for energy-generation faced by these economies, low-energy processing systems need to be developed for sustainable operation and regular production of FS-based fertilizer, especially in farming areas.

Linking urban sanitation infrastructure and service provision to city development can draw sufficient financial resources for building infrastructure and securing operation and maintenance costs, as city planners might see the direct economic benefits of recycling. It is also an opportunity to close the nutrient loop in urban excreta and wastewater management. Such a linkage can be established with agriculture, which contributes an important share to urban food supply.

In the years to come, more than 2.6 billion people without access to improved sanitation will have to be serviced (WHO and UNICEF, 2006). The majority will likely use on-site sanitation, the predominant option in developing countries. Considering this, it can be assumed that for decades to come growing quantities of FS, dehydrated faeces and urine will have to be dealt with.

Thus, the goals and requirements of human waste or FS collection and treatment systems can be summarized as follows:

- recovery of nutrients and biosolids;
- removal of micropollutants;
- increase the concentration of nutrients;
- sanitizing of faecal sludge for reuse;
- economical, energy efficient and market-driven implementation.

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