Technology

Chapter 8

Planted Drying Beds

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Learning Objectives

- Know what a planted drying bed for sludge dewatering is.
- Have an overview of the vegetation types that may be used, the role they play in sludge dewatering and criteria for their selection.
- Know the appropriate level of operational and maintenance monitoring necessary for the operation of planted drying beds.
- Be able to design a planted drying bed to achieve the desired treatment objectives.

8.1 INTRODUCTION

Planted drying beds (PDBs), also sometimes referred to as planted dewatering beds, vertical-flow constructed wetlands and sludge drying reed beds, are beds of porous media (e.g. sand and gravel) that are planted with emergent macrophytes. PDBs are loaded with layers of sludge that are subsequently dewatered and stabilised through multiple physical and biological mechanisms (Kadlec and Knight, 1996).

PDBs were initially developed to stabilise and dewater sludge from small activated sludge treatment plants in Europe and US (Kadlec and Knight, 1996; Lienard and Payrastre, 1996; Nielsen, 2003). This technology has also been successfully adapted in other parts of the world for use with various types of sludge, including faecal sludge (FS) from onsite sanitation technologies. In northern climates, PDBs have been shown to achieve higher rates of water removal, solids reduction and increased oxidation in the summer compared to winter (Edwards *et al.*, 2001), thus making them ideal for tropical countries where there is less climactic variation and more constant solar radiation. Since 1996, SANDEC/EAWAG (The Department of Water and Sanitation in Developing Countries at The Swiss Federal Institute of Aquatic Science and Technology) and their research partners have jointly undertaken field experiments to determine treatment efficiencies and to establish the design and operational guidelines of pilot beds treating FS from onsite sanitation technologies. A pilot-scale facility has been operating successfully in Thailand for nearly a decade (Koottatep *et al.*, 2005) while in Africa, trials at yard-scale have been conducted at the University of Yaoundé I (Cameroon, Figure 8.1) and at full scale at the Cambérène Treatment Plant in Dakar, Senegal (EAWAG/SANDEC, 2009; Kengne *et al.*, 2008).

Although there are limited examples of full-scale PDBs treating FS in operation, current research has produced promising results and it is expected that PDBs will be adopted more extensively around the world, especially in tropical regions of low-income countries.

FS is repeatedly loaded onto PDBs, with up to 20 cm of FS per loading (Kadlec and Wallace, 2009), where it accumulates for several years depending on the loading rate, the capacity of the system and mineralisation rates (Nielsen, 2003). Due to the limited number of existing operational beds and the variety of operational conditions, it is currently difficult, if not impossible to give a single value or precise range for the duration of sludge accumulation. Long-term bed permeability is maintained by the dynamic system of percolation canals created by the continuously growing root system of the plants. The volume of sludge on the PDB reduces continuously (through moisture loss and degradation), and the plants maintain porosity in the sludge layer thereby significantly reducing the need for sludge removal compared to unplanted drying beds (which require sludge removal every two to three weeks) (Strauss *et al.*, 1997). Emergent macrophytes are therefore essential to the improved performance for stabilisation, pathogen reduction and clogging of PDBs over unplanted drying beds.

The dewatering, organic stabilisation and mineralisation performance of the PDB depends on a variety of factors such as the media type and size, the type of plants, the maturity of the beds, climatic factors, and the sludge characteristics, as well as operational factors such as the hydraulic loading rate (HLR), the solids loading rate (SLR), and the loading frequency (Breen, 1997; Prochaska *et al.*, 2007; Van Cuyk *et al.*, 2001). As the bed matures, microbial communities become more established and stable. The following sections discuss, in detail, the operational conditions and design parameters which currently define the best practice for PDBs used for FS .

Figure 8.1 Pilot-scale planted drying beds for faecal sludge treatment at the University of Yaoundé I (photo: Linda Strande).

8.2 MACROPHYTES

Macrophytes are plants found in wetlands, marshes and swamps, and are distinguished by their ability to grow when partially or fully submerged in water. There are four types of macrophytes: freely floating, submerged, floating leaved and emergent. Freely floating macrophytes have leaves that float on the surface of the water, usually with submerged roots. Submerged macrophytes are usually rooted in the bottom soil with the vegetative parts predominantly submerged. Floating leaved macrophytes are those that are rooted but have floating leaves, while emergent macrophytes are rooted in soil below shallow water with the leaves and stems emerging above the surface of the water.

While macrophytes produce many seeds, reproduction by germination does not generally take place due to the hindering aquatic conditions (Hutchinson and Dalziel, 1972). Successful reproduction usually occurs by way of cuttings, stolons or rhizomes. Rhizomes are dense, underground stems from which vertical shoots grow upward, and from which roots grow out and down. On the stem, new buds form at nodes and the space between the nodes is termed the internode. The rhizomes are important as they provide a large surface area for bacteria to grow on; and in PDBs bacteria are responsible for the degradation of organics and mineralisation of sludge. The rhizosphere is the area surrounding the rhizomes which has a higher concentration of oxygen due to release by the roots (Section 8.3.2). Figure 8.2 shows schematic diagrams of the rhizomes and the node and internode structure that are typical of macrophytes.

Emergent macrophytes are generally the best suited for PDBs because they are the most productive of all aquatic macrophytes. In other words, the rate of multiplication and generation of new biomass is very high. They can establish and extend their roots and rhizomes through the sludge layers while the stem continues to grow up through the accumulating sludge layer. Leaves growing above the sludge layer are able to make use of solar radiation for photosynthesis and transpiration.

Figure 8.2 Left: rhizome structure of *E. pyramidalis* showing roots and two newly formed buds; Right: application of faecal sludge on drying beds with young shoots that have nodes and internodes (photos: Ives Kengne).

Although a variety of macrophytes exist in nature, there are a limited number of emergent macrophytes that grow well under PDB conditions, which vary between aerobic, anoxic and anaerobic (depending on the loading), with the added burden of variable pH, salinity, and high nutrients (De Maeseneer, 1997; Uggetti *et al*., 2012). The high and highly variable nutrient levels in sludge means that any plant used in a drying bed must be able to tolerate a wide range of growing conditions and must be able to withstand the shocks associated with sludge loading and drying. Sludge from public toilets, for example, is high in salts (conductivity up to 15 mS/cm) and ammonia (2 to 5,000 mg/L), which are toxic to most plants (Clarke and Baldwin, 2002). To offset these potentially lethal conditions, public toilet sludge must be diluted with sludge that has lower concentrations of salt and ammonia (e.g. from septic tanks) in order to provide conditions that are suitable for the specific type of macrophytes growing in the drying beds.

In European applications, reeds (*Phragmites sp.*) and cattails (*Typha sp.*) are the most common types of emergent macrophytes used in PDBs (Kadlec and Knight, 1996; Kim and Smith, 1997; Koottatep *et al*., 2005). *Phragmites australis* is an invasive species and its use is restricted in the US and New Zealand (Uggetti *et al*., 2012). Other indigenous options are currently being explored such as antelope grass (*Echinochloa sp.*) and papyrus (*Cyperus papyrus*). Based on preliminary testing, both of these show promising results for use in PDBs.

A macrophyte that is to be used in PDBs should have the following characteristics (De Maeseneer, 1997):

- fast growing under diverse conditions;
- high transpiration capacity;
- tolerance to different water levels and drought conditions;
- tolerance to extremes of pH and salinity;
- deep growing rhizome and root system;
- ability to build new roots on the nodes when they become encased in sludge; and
- readily available, indigenous and non-invasive

Although *Phragmites australis* (reeds) is the most frequently used species in PDBs (De Maeseneer, 1997; Hardej and Ozimek, 2002), there are potentially many other local, untested species with these characteristics that are capable of achieving similar, if not improved levels of treatment. A summary of the most commonly used macrophytes for FS treatment is presented in Table 8.1.

Table 8.1 Macrophytes commonly reported for the treatment of faecal sludge (Kengne *et al*., 2008; Nielsen, 2005; Koottatep *et al*., 2005)

Plant species	Common name	Water type	Habitat	Water regime
Phragmites sp.	Reeds	Fresh to brackish	Marshes; swamps	Seasonal to permanent inundation, up to 60 cm
Typha sp.	Cattail	Fresh to marshes	Pond margins	Seasonal to permanent inundation, up to 30 cm
Cyperus papyrus	Papyrus	Fresh to marshes	Pond margins, lakes	Seasonal to permanent inundation, up to 30 cm
Echinochloa sp.	Antelope grass	Fresh to brackish	Marshes; swamps	Seasonal to permanent inundation, up to 40 cm

8.3 TREATMENT MECHANISMS

The treatment of sludge in PDBs is achieved through a combination of physical and biochemical processes. In wet, rainy climates, macrophytes play an essential role in almost all processes, and are responsible for the higher levels of treatment in terms of stabilisation and pathogen removal in PDBs compared to unplanted drying beds (Brix, 1997; Kadlec and Knight, 1996). Macrophytes therefore play an essential role in the following:

- stabilising the beds to prevent media erosion and clogging, and improving the drainage;
- increasing moisture loss (through evapotranspiration, in contrast to only evaporation in unplanted drying beds);
- providing a surface area for microbial growth within the sludge layer;
- transferring oxygen to the sludge layer (i.e. within the rhizosphere); and
- absorbing heavy metals and nutrients.

However, while PDBs, and their ability to wick away moisture via transpiration, make them an applicable technology in humid or rainy climates, the macrophytes of a PDB could wilt and die off in a climate that is too hot and dry, especially if the sludge does not provide sufficient moisture. However, if the PDB can be operated to induce 'ponding', i.e. keeping a certain amount of water in the beds by turning off the drainage outlet valve of the ponds or by adjusting the level of the outlet valve, then PDBs can be operated efficiently, even in a very dry climate.

The following sections explain the key treatment mechanisms that occur in PDBs and the ways in which macrophytes assist in these processes. This information should be weighed against the other technology options presented in this book, and the appropriate technology solution should be selected based on site-specific conditions (Chapter 17).

8.3.1 Infiltration (percolation)

When sludge is applied on the beds, solids are retained on the surface of the filtering matrix (either the porous substrate or the existing sludge layer), while the liquid drains vertically through the media where it is collected for further treatment (Kadlec and Knight, 1996). One of the main operational concerns with unplanted drying beds is the formation of erosion channels which can lead to short-circuiting and uneven treatment. However, in PDB, the dense macrophyte root system impedes erosion and helps to stabilise the sludge layers. The natural movement of the plants due to wind, and the growth of roots encourage water to drain around the stems and the tubular spaces created around them, thereby leading to improved drainage. As macrophytes grow, they break up and loosen the accumulating sludge, which also maintains good conditions for filtration (Brix, 1994). When macrophytes die, the decaying roots and rhizomes leave behind small pores and channels which allow infiltration and circulation of air, and encourage aerobic conditions (Brix, 1994).

8.3.2 Evapotranspiration

Transpiration is the process by which water is lost into the atmosphere from the leaf and stem surfaces of the plant. The presence of macrophytes therefore aid in sludge drying by absorbing and then releasing moisture via transpiration. In temperate climates, evapotranspiration (the sum of evaporation and transpiration) rates of up to 2.5 cm/day can be achieved in reed stands on very hot days. (De Maeseneer, 1997). The rate could be even higher in tropical regions depending on climatic conditions such as wind speed and relative humidity. Evapotranspiration from the macrophytes results in increased moisture loss and volume reduction, compared to unplanted drying beds. In one study a comparison was made between PDB and unplanted drying beds using sludge from a biological wastewater treatment plant. The PDB achieved over 95% volume reduction over a year (6 months loading, 6 months resting) with a total sludge loading depth of up to 493 cm, while the unplanted drying beds; achieved less than 90% reduction in volume. Dry matter content for the same beds, reached up to 69% for the PDBs while the unplanted beds achieved only 31%. This increased performance in PDBs is thought to be due to evapotranspiration and percolation of the macrophytes (Stefanakis and Tsihrintzis, 2012a). While sludge from wastewater treatment plants is not necessarily directly comparable to unstabilised FS, the majority of the PDB research has been conducted on wastewater sludge and these results are therefore used to provide examples throughout this chapter.

8.3.3 Stabilisation/mineralisation

Stabilisation (also referred to as humification) is the conversion of organic matter into more stable, organic components. Mineralisation is the process by which biologically available inorganic nutrients are released during the degradation of organic material (e.g. the degradation of amino acids results in the release of ammonia). The process of stabilisation and mineralisation leads to the release of inorganic nutrients, which are essential plant and microbial nutrients, thereby contributing to improved fertility of the macrophytes. Even FS that has undergone bacterial decomposition for years (e.g. in a septic tank), may require further stabilisation if it still has a high BOD. Stabilisation also reduces the odour of the sludge and destroys the pathogenic organisms. For instance, storage time has been found to contribute to weakening the external membranes of helminth eggs, which may be degraded by bacteria and fungi present in the sludge layer (Sanguinetti *et al.*, 2005).

The surface of rhizomes provide attachment areas for bacteria and other microorganisms, and the resulting microbial density and activity can lead to improved sludge mineralisation as well as improved water and nutrient uptake (Bialowiec *et al.*, 2007; Brix, 1997; Chen *et al.*, 2007; Gagnon *et al.*, 2007).

Metrics of mineralisation are not universally agreed upon. However indicators of the degree to which sludge on a PDB has been mineralised are the reduction in total volatile solids (TVS) and the ratio of TVS to total solids (TS) content, which indicate the change in readily degradable material. Mineralisation primarily takes place during resting periods between sludge loadings as it occurs more rapidly in aerobic conditions. When sludge is applied to the beds, oxygen is less available due to the water saturated conditions and high concentrations of biodegradable organic matter. One study using sludge from a biological wastewater treatment plant showed that the VS content of the sludge was reduced from 0.74 VS/TS to 0.59 VS/TS (Stefanakis and Tsihrintzis, 2012a) while another showed a final value of 0.52 VS/TS (Uggetti *et al.*, 2012). The VS content has been found to be much lower in the lower layers of the sludge bed compared to the upper layer, due to the increased retention time in the bottom layers leading to increased oxidation (Stefanakis *et al.*, 2009).

8.3.4 Oxygen transfer

Untreated FS contains little, if any, dissolved oxygen and is therefore generally anoxic or anaerobic. However, oxygen can be transferred into the sludge through various physical and biological mechanisms and create anoxic and aerobic zones. These varying concentrations of oxygen allow for complex processes (e.g. nitrification and denitrification) to occur in the PDB leading to improved levels of treatment compared to unplanted beds.

Rooted macrophytes have adapted to growing in water-saturated soil, where the pore spaces are filled with water and the conditions are anaerobic. Macrophyte roots obtain oxygen through an internal transfer system that moves oxygen from the leaves and stems down into the roots and rhizomes. The internal lacunar (circulatory) system may occupy up to 60% of the total tissue volume, depending on the species (Brix, 1994). Some of the oxygen that arrives at the root is leaked into the rhizosphere. This leaked oxygen then creates aerobic conditions in the immediately surrounding area, which supports a variety of aerobic bacteria, and helps promote aerobic degradation and nitrification. Leakage occurs primarily at the root-tip and the rate of oxygen release depends on the permeability of the root-walls, and the internal oxygen concentration among other factors. This rate is difficult to quantify, but oxygen release rates from roots of *Phragmites* have been calculated between 0.02 and12g/m^2/day (Brix, 1994).

As the top layer of sludge dries, it cracks, thereby creating gaps through which oxygen can further penetrate the sludge layer (Figure 8.3). These cracks are more pronounced in hot, arid climates, and are predominant in areas of the beds containing few rhizomes as the rhizomes hold the sludge together (Stefanakis and Tsihrintzis, 2012a). Hot, dry conditions are therefore beneficial for crack-induced oxygen transfer, yet extreme conditions could cause plants to wilt and die. This emphasises that the technology choice of planted or unplanted drying beds needs to be carefully chosen given the local conditions.

8.4 PERFORMANCE INDICATORS

The performance efficiency of a PDB is usually judged based on water content, the quantity and form of nutrients, and the degree of stabilisation and pathogen removal of the treated sludge. The following sections explain in more detail how these performance indicators are measured and assessed, and two case studies (Thailand and Cameroon) are presented to illustrate realistic performance data that has been achieved in the field.

8.4.1 Dewatering

Sludge dewatering refers to the removal of water from sludge for improved handling and reuse. This is generally assessed by measuring the TS concentration. Total solids (or dry matter) are one of the key design parameters for FS treatment plants (FSTPs). In tropical regions, it is possible to achieve dry matter (DM) percentages of at least 30% (Kengne *et al.*, 2009a) by treating sludge on PDBs.

Figure 8.3 An example of the formation of cracks in sludge dryings beds planted with *E. pyramidalis* (photo: Ives Kengne).

8.4.2 Nutrient removal

The fate of nutrients in FS treatment is very important as it will determine the enduse opportunities of the sludge and the treatment required for the effluent. Nitrogen (N) and phosphorus (P) can be recovered for beneficial enduses, but also have potentially damaging effects on surface and ground water if discharged to the environment. One study where sludge from a biological wastewater treatment plant was treated on a PDB showed that with an SLR between 30 and 75 kg dm/m^2/year, total Kjeldahl nitrogen (TKN) was reduced by 35 to 42% from an initial level of 55 mg TKN/g DM, compared to a 24% reduction in an unplanted drying bed, thereby indicating the role of macrophytes in nutrient cycling. It is thought that the main processes of nitrogen transformation in PDBs include uptake and assimilation by plants and microbiota, volatilisation, and denitrification in anaerobic zones (Kadlec, 2009). The macrophytes also play other roles in denitrification, for example as a carbon source and attachment sites for denitrifying microorganisms. Phosphorus removal, on the other hand, is found to be fairly similar between planted and unplanted beds; the primary removal mechanism for phosphorus appears to be sorption onto the porous media and plant roots (Stefanakis and Tsihrintzis, 2012a).

Plant uptake of nitrogen and phosphorus from PDBs was shown to range between 0.2% and 5% of the total nutrient load depending on climactic conditions, loading rates, and other factors (Stefanakis and Tsihrintzis, 2012a). Although no specific data for PDBs exists, nitrate reduction in constructed wetlands can account for 60 to 70% of nitrogen loss (Cooke, 1994) and similar removal rates could be expected in PDBs depending on the level of water saturation.

Nutrient recovery is achieved through plant uptake and subsequent harvesting. If the plants are allowed to die and decompose on the bed surface, the nutrients will be recycled back into the sludge. Harvesting the plants and using them for fodder or other beneficial uses is one of the main benefits of PDBs. A study conducted in Cameroon in PDBs vegetated with papyrus (*C. papyrus*) and antelope grass (*E. pyramidalis*) showed that the annual papyrus harvest generated 20 to 30 dry t/ha above-ground biomass, whereas the below-ground biomass varied between 80 and 150 dry t/ha (rhizomes are left in place for continued growth). A full harvest of *E. pyramidalis* shoots three times a year generated an annual biomass of at least 100 to 150 dry t/ha, as opposed to a below-ground biomass of 30 to 70 dry t/ha. By harvesting the plants, between 236 and 383 g N/m^2/year and 60 to 92 g P/m^2/year is removed from the PDBs in the case of papyrus, and between 216 and 330 g N/m^2/year and 55 to 84 g P/m^2/year for the aerial plant parts of the antelope grass. The removal of roots and rhizomes during desludging will generate an additional 55 to 124 g N/m^2/year and 33 to 36 g P/m^2/year (Kengne *et al*., 2008).

Phosphorus that is not in the leachate is mainly present as particulate forms in the sludge layer, or absorbed onto the media and root system. Nitrogen is mainly removed through nitrification and denitrification processes, both of which are increased in the presence of plants, which explains the increased treatment performance of leachate in PDB.

Case Study 8.1 : Loading frequency experiments in Thailand
(Adapted from Koottatep *et al.*, 2005)

Drying beds planted with cattail (*Typha*) were used in Bangkok, Thailand as a treatment for FS with average concentrations of 15.4 g/L TS, 18.7g/L COD, 1.1 g/L TKN and 0.4 g/L NH_3-N.

With a sludge loading rate that varied between 80 and 250 kg TS/m^2/year, removal efficiencies were found to range from 66 to 88% TS, 78 to 99% TCOD, 82 to 99% TKN and 40 to 98% NH_3-N. Approximately 65% of the liquid passed through the under drain to produce a leachate with concentration ranges of 1.9 to 6.01 g/L TS, 0.1 to 2.2 g/L TCOD, 0.006 to 0.25 g/L TKN, and 0.005 to 0.2 g/L NH_3-N. The remaining 35% of liquid was lost through evapotranspiration or retained in the accumulated sludge layer.

Varying the loading frequency between one and three times a week did not significantly impact the treatment performance, but loading twice a week assisted in supporting the growth of cattails without having to retain the leachate in the beds (which is achieved by closing the outlet valve to prevent drainage). However, in order to minimise the workload associated with the feeding, application was undertaken once a week and leachate retention was introduced as a permanent measure. This provided adequate moisture for the cattails to prevent wilting during dry weather.

Case Study 8.2: Loading rate experiments in Cameroon
(Adapted from Kengne *et al.*, 2011)

In Cameroon, experiments using FS from various onsite sanitation facilities (i.e. septic tank, public latrines and traditional pit latrines) were conducted using loading rates of 100 kg/m^2/year and 200 kg/m^2/year for *C. papyrus* and *E. pyramidalis*. The results showed that when the beds were loaded once a week the loading rate had no significant impact on the dewatering performance. On average, the concentrations of TS and TSS decreased from 3.7% and 27.6 g/L in the raw sludge to less than 0.5% and 2.1 g/L in the leachate, respectively. COD concentrations were reduced from 31 g/L in the raw sludge to less than 0.8 g/L in the leachate, while NH_4^+ was reduced from 0.6 g/L to less than 0.09 g/L. The TKN concentration in the leachate averaged between 0.1 and 0.2 g/L. Good nitrification was achieved with an average concentration of between 0.2 to 0.5 g/L, probably due to an increase of the oxygen concentration when passing through the filtering media.

Beds loaded with 100 kg TS/m^2/year rarely clogged and had an average dry matter content of more than 30%. Approximately 50% of the applied sludge volume was collected as leachate. Loading rates greater than 200 kg TS/m^2/year, resulted in a greater occurrence of clogging in the papyrus beds than those of *E. pyramidalis*, leading to decreased drainage of leachate from the beds.

8.4.3 Fate of heavy metals

In general, FS should not have high concentrations of heavy metals, unless the sludge receives discharge from industrial sources (Kroiss, 2004; Molla *et al* , 2002; Towers and Horne, 1997). Low concentrations of metals like chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu), nickel (Ni), manganese (Mn), zinc (Zn), and iron (Fe) can be present in FS from additives added to onsite technologies, chemicals or batteries disposed of into the systems, exposure to contaminants from trucks that also transport industrial sludge, or because they are consumed and excreted by humans.

Research conducted using *Phragmites australis* and treated sludge from an activated sludge wastewater treatment plant found that the metals Cr, Cd, Pb, Cu, Ni, Mn, Zn, and Fe partitioned unevenly throughout the PDB, and did not accumulate in the macrophytes at significant levels. The metals were taken up in unequal quantities by the plants in decreasing order of Cr > Fe > Zn > Mn > Cu > Pb > Ni > Cd. The reeds were found to be fairly tolerant to metal concentrations and did not show any signs of toxicity, despite absorbing slightly increasing amounts of metals each year. Analysis showed that the metals were most concentrated in the roots, followed by leaves and stems. The quantities absorbed by the plants were however not significant and accounted for less than 3% of the total metal concentrations in the sludge (Stefanakis and Tsihrintzis, 2012b).

During treatment the concentration of metals in sludge typically increases as the organic matter is reduced through decomposition. However, in one study, the filter bed media was found to be the biggest sink of metals, accounting for 47% of the influent content. Sedimentation, adsorption and precipitation (as metal oxides, carbonates, and sulphides) are the primary mechanisms through which the gravel and sand layers trap and retain metals as they pass through the bed. It was found that only 16% of the influent metals were present in the leachate (Stefanakis and Tsihrintzis, 2012b).

8.4.4 Pathogen removal

When identifying the quality of sludge that can be used for a particular enduse, a multi-barrier approach for pathogen removal is followed rather than the application of strict limits. For example, sludge that is to be used as a fuel for combustion or for growing animal forage, does not require the same degree of pathogen reduction as sludge that has the potential to come into contact with crops for human consumption. Chapter 10 (Enduse of Treatment Products) addresses this issue in further detail.

The primary concern for sludge that is to be used in agriculture is pathogen content. Predation, dehydration and retention time are the main mechanisms in PDBs that result in pathogen reduction in FS, an increase in pathogen reduction comes with an increase in retention time. Helminth eggs are very resistant to environmental stress (e.g. dehydration and heat) and are an important indicator of sludge quality. Ingallinella *et al* ., (2002) summarise various reports and show that treatment of FS in a PDB reduced the concentration of Helminth eggs from between 600-6000 helminth eggs/ L of FS to 170 eggs /g TS, with an egg viability of between 0.2 and 3.1% (Ingallinella *et al* , 2002). Other research showed that PDBs were able to achieve a complete elimination of helminth eggs in the leachate, but not in the solids, where 79 helminth eggs/g TS were measured (Kengne *et al* ., 2009b).

8.4.5 Other considerations

Apart from this direct role in FS treatment, macrophytes are aesthetically pleasing and may provide a habitat for a range of wildlife like birds and reptiles (Brix, 1994). However, the presence of insects and other disease vectors (e.g. rodents, mosquitoes) could pose potential health hazards if not properly managed. Communities surrounding PDBs are generally more accepting of a treatment technology that appears to be 'natural' and in many cases, may not even be aware that the PDB is in fact artificial and used for FS treatment (De Maeseneer, 1997). Therefore, although there are no direct measurements for appearance, an additional advantage of PDBs is the aesthetic one which should be taken into account when selecting a treatment technology.

Table 8.2 summarises the performance indicators of PDBs observed under a variety of experimental conditions.

Table 8.2 Summary of performance indicators of planted sludge drying beds around the world

Country	SLR (kg TS/ m^2/year)	% Solids and moisture reduction	% Nutrients and organics	Other metrics	Plant used	References
France[1]	≈ 70	85% (TS)	70% (COD) 79% (TKN) 66% (NH_4-N)		*Phragmites australis*	Lienard and Payrastre, 1996
USA[1]	9.8-65	99% (TSS)	95% (COD) 90% (TKN) 42% (NH_4-N)		*Phragmites australis*	Burgoon *et al.*, 1996
USA[1]	16-106	46-49% (TVS) 15-47% (TS)			*Phragmites australis*	Kim and Smith, 1997
Poland[1]	-	94.6% (volume reduction), 43-65% (moisture content)			*Phragmites australis*	Obarska-Pempkowiak *et al.*, 2003
Thailand[2]	250	74-86% (TS) 96-99% (SS) 20-25% (DM content of dewatered sludge after 4 years)	78-99% (COD) 70-99% (TKN) 50-99% (NH_3)	< 6 viable helminth eggs/g of TS	*Typha augustifolia*	Koottatep *et al.*, 2005
Cameroon[2]	200	70.6-99.9% (TS) 78.5-99.9% (SS) 30% (DM content of dewatered sludge)	73.4-99.9% (COD) 69.2-99.3% (TKN) 50-99% (NH_3)	100% (helminth eggs)	*Echinochloa pyramidalis*	Kengne *et al.*, 2009
Senegal[2]	200	97% (TS) 99% (SS) 99% (DCO)	91% (NH_4^+) 97% (PO_4^{3-})		*Echinochloa pyramidalis*	Tetede, 2009

[1] Wastewater sludge [2] Faecal sludge

8.5 DESIGN AND CONSTRUCTION

Despite early successes with PDBs in Europe, and recent experiments with FS in low-income countries, PDBs for the treatment of FS are still in the early stages of development. Little research has been conducted with full-scale, operational plants. Few systems have been adequately monitored or have not been operating long enough to provide sufficient data that also allow for definitive design and construction guidelines. A number of design and operational uncertainties cannot be clarified until further research is conducted, and operating experience is compiled. However, it is currently accepted that the design should attempt to mimic PDBs used for treatment of wastewater sludge.

Construction costs are generally lower than for conventional sludge treatment technologies, and PDBs require less space than waste stabilisation ponds. Though mechanically simple (there are few moving parts) the technology requires careful design, construction and acclimatisation in order to achieve adequate results. Table 8.3 lists the general design considerations that should be taken into account for the construction of PDBs based on the results of existing plants. An example of a PDB design is provided in Case Study 3.

Table 8.3 General design considerations for the construction of planted drying beds (adapted from Davis,1995)

Factor	Parameters to consider	Remarks
Site selection	Land use and access	• Located centrally to reduce transport distances • Located away from dwellings to avoid odours or insects from spreading • Located with adequate truck access and away from residential areas to reduce noise
	Land availability	• Site should be large enough to accommodate present requirements as well as any future expansion
	Site topography	• Select (whenever possible) a site that will allow for gravitational flow to reduce energy and pumping costs
Structure	Cells	• Excavate basins or build up earth embankments around cells to create depth • A freeboard should be high enough to allow accumulation of sludge over a period of at least 3 to 4 years. A freeboard of 1.5 to 2 m is generally recommended • Multiple cells (in parallel) are recommended so that cells can be loaded sequentially and allow for a resting phase • Dykes can be used to separates cells and to avoid short-circuiting • The bottom should be sloped slightly (1-3%) • Allow for space between cells for machinery and maintenance activities (e.g. plant harvesting, sludge removal, etc.)
	Liners	• Must be sealed to avoid possible contamination of groundwater or intrusion of water into the beds. Synthetic liners are preferable, but compacted clay can also be used
Flow structures	Inlet	• Flow control structures should be simple and easy to adjust. Channels or gated pipes are generally used
	Outlets	• A weir, spillway or adjustable riser pipe should be installed to allow for the adjustment of water levels if necessary (i.e. to retain water in the cell to avoid plant wilting)
System life		• The operational life of the beds is determined by the loading rate, stabilisation rate and the number of beds. The number of beds should be determined based on the expected amount of sludge to be treated
Climate and weather		• Retaining water in the cells may be necessary to avoid the side effects of drought and high temperature (see "Outlets" above) • Increase the resting period (time between two consecutive loadings) when there is excessive rainfall
Filter matrix (substrate)		• Substrates can include sand, gravel (medium to coarse rock) or other coarse media • The upper substrate layer should have a coefficient of uniformity higher than 3.5 to avoid rapid clogging (this can be achieved after sieving or washing to remove fine particles) • A small amount of soil or organic material may be required to allow the growth of plants during the early stages • The bed must be kept moist, but not flooded until seeds have germinated or rhizome fragments produce new shoots
Vegetation		• Choose indigenous, non-invasive macrophytes that have been proven to grow on sludge • Select shoots or fragments with no visible signs of nematode attack • Plant or harvest in the rainy season to assist with growth or regrowth
Ventilation		• Increased air flow as well as better hydraulic flow conditions of the liquid can be achieved using hollow blocks or ventilation pipes*
Feeding system		• Uniform sludge distribution (preferably in the middle of the beds) avoids dead zones and uneven plant growth • Feeding should occur one to three times a week, depending on the season

* Comparative studies that examined the effect of installing aeration pipes (perforated PVC columns to convey air through the bed layers) found that they did not directly improve the dewatering process, although they did assist with plant growth, which improves evapotranspiration (Stefanakis and Tsihrintzis, 2012a). PVC columns may therefore be included in a PBD design, although they are not necessary.

Case Study 8.3: Design and construction of a planted drying bed in Thailand

In 1996, the Asian Institute of Technology (AIT) in collaboration with SANDEC/EAWAG, constructed a pilot-scale PDB to treat FS produced in Bangkok. This FS treatment scheme was comprised of the following units; i) screening for pre-treatment (retention of coarse material); ii) balancing and mixing tank (to achieve a certain degree of homogenisation of sludge from various sources); and iii) three PDBs attached to a waste stabilisation pond and a vertical-flow constructed wetland bed for leachate polishing. Each of the PDBs measured 5 m × 5 m at the surface of the filter bed (and 6.2 m x 6.2 m at the rim of the freeboard) and was lined with ferro-cement.

The depth of the filter media was designed to be 65 cm to prevent protrusion of the cattail roots and rhizomes through the bottom of the media (root length is between 30 and 40 cm). A 10 cm layer of fine sand, 15 cm layer of small gravel, and 40 cm layer of large gravel (from top to bottom) were used to create the filter matrix in each PDB unit. A freeboard height of one meter was allowed for the accumulation of the dewatered sludge. Narrow-leaf cattails (*Typha augustifolia*), collected from a nearby natural wetland, were planted on top of the sand layer in each bed unit at an initial density of 8 shoots/m^2. An underdrain and ventilation system consisting of hollow concrete blocks, each with a dimension of 20 cm x 40 cm x 16 cm and perforated PVC pipes with a diameter of 20 cm were installed at the bottom of the bed, under the filter media. Ventilation pipes of the same diameter were mounted on the drainage system and extended approximately one meter over top edge of the units to take advantage of natural draught ventilation to provide increased oxygen into the sludge layer and help reduce anaerobic conditions. The leachate of each PDB unit was collected in a 3 m^3 concrete tank for sampling and analysis.

Figure 8.4 A currently out of use pilot-scale drying bed at the Asian Institute of Technology (AIT), showing ventilation pipes (photo: Linda Strande).

Table 8.4 Summary of design elements used for faecal sludge planted drying beds in Thailand

Component	Details
Bed slope	1-3%
Side slope	50-100%
Drainage system	Coarse gravel, hollow concrete blocks or perforated pipes
Ventilation	Ventilation pipes connected to the drainage system
Filter Material	From bottom to top Large gravel (dia. = 5 cm) at a depth of 45 cm Medium gravel (dia. = 2 cm) at a depth of 15 cm Sand (dia. = 0.1 cm) at a depth of 10 cm
Vegetation	Cattails *(Typha augustifolia)*
Freeboard	1.0 m
Feeding system	Uniform distribution (in the middle of bed units)
Pre-treatment	Coarse bar screen

8.6 OPERATION AND MAINTENANCE

As with any treatment technology, proper operation and regular maintenance are essential for optimum performance and improved life span. An operating cycle generally consists of a start-up phase with reduced loading to acclimatise the plants, followed by loading at the design rate with intermittent plant harvesting and desludging. These aspects are discussed in the following sections.

8.6.1 Commissioning/ start-up

PDBs are technically simple, but biologically complex and must therefore be carefully operated during start-up to ensure that the macrophytes have a chance to acclimatise to growing under conditions of high-strength FS. During the start-up phase, the beds should be irrigated with untreated wastewater or diluted FS. One study found that during commissioning of a PDB with agricultural (pig) slurries, macrophytes were loaded with 25 mm of sludge twice in one month, 8-months after being planted. This time frame for acclimisation and low sludge loading rate (3 kg TS/m^2/year) was found to be sufficient to prepare the macrophytes for the full loading regime (Edwards *et al.*, 2001). Planting macrophytes during the rainy or wet season is also recommended to help the macrophytes endure the commissioning phase. Depending on the climate and operational conditions, a start-up phase lasting from months to an entire year can be necessary before loading the bed at the design loading rates. On average, a 6 month start-up is recommended (Kengne *et al.*, 2011). Cattails have been found to be more sensitive than reeds during the commissioning phase and may need extra time before they can withstand full loading. However, as shown in Case Study 8.3, two to three months has been adequate for acclimisation (Stefanakis and Tsihrintzis, 2012a). Plant density is another important factor and planting rates can vary from 4 plants/m^2 to 12 plants/m^2 (Edwards *et al.,* 2001). Only vigorous and young shoots, free of parasites, should be selected for the PDBs to ensure that the macrophytes survive and thrive. As the plants develop and increase in density, so too will the evapotranspiration rates (Stefanakis and Tsihrintzis, 2012a). Case Study 8.4 presents two examples of PDB commissioning conditions in West Africa.

Case Study 8.4: Commissioning planted drying beds in West Africa
(Adapted from SANDEC/EAWAG, 2009)

In Cameroon, young shoots, or fragments of *E. pyramidalis* shoots, having at least one internode, and old fragments of rhizomes of *C. papyrus* weighing 300 to 350 g (fresh weight) were allowed to grow for 6 weeks in the media saturated with raw domestic wastewater prior to sludge application. FS was applied over the next 6 months in increasing concentrations before reaching the full loading rate of 100 to 200 kg TS/m^2/yr (Kengne *et al*., 2011). The plant density before sludge application was 11 shoots per m^2 for *E. pyramidalis* and 9 rhizomes (with 1 to 4 shoots/rhizomes) per m^2 for *C. papyrus*.

In Senegal, the starting phase for a full scale PDB with *E. pyramidalis* took four months during which time the beds were loaded with the supernatant from a FS settling-thickening tank. After this time, the PDBs were loaded with FS with a concentration ranging from 13 to 235 kg/m^2/year. Plant densities at the start up ranged from 9 to 12 shoots/m^2.

8.6.2 Loading rates and sludge accumulation

Before loading the beds, vacuum trucks should discharge the sludge into a holding-mixing tank that is fitted with a bar screen to retain coarse material and garbage and prevent it from clogging the bed. Furthermore, the tank has the benefit of acting as a buffering unit to regulate the flow of sludge onto the bed; some type of holding-mixing unit should always be installed before the bed is loaded.

Figure 8.5 A holding -mixing tank with a bar screen is used in Senegal to prevent garbage from clogging the bed (photo: Linda Strande).

Data on PDBs operating at nominal loading rates vary according to area, and indicate the importance of climate on the operating parameters. In general, hot, dry conditions that allow for increased rates of evapotranspiration allow for increased sludge loading rates. In Europe, loading rates with wastewater sludge have generally been low (not more than 80 kg/m^2/year), while results from FS treatment in tropical countries have revealed that PDBs can be loaded with almost three times this amount. For example, a series of experiments conducted at AIT with FS, showed that a cattail-based PDB was operated with up to 250 kg/m^2/year (Koottatep *et al.*, 2005). Similarly, in Dakar, trials of PDBs vegetated with *E. pyramidalis* performed well when loaded with FS at concentrations of up to 235 kg/m^2/year. In Cameroon, treatment of FS at yard scale show that a PDB planted with *C. papyrus* could be operated efficiently at 100 kg/m^2/year while a bed planted with *E. pyramidalis* could be loaded with 200 kg kg/m^2/year. However, attempts to increase the loading to 300 kg/m^2/year generally resulted in severe clogging of beds (Kengne *et al.*, 2011). Between 1996 and 2003, experimental drying beds were operated at the Asian Institute of Technology (AIT) in Bangkok, Thailand and the solids (kg TS/m^2) were monitored in the dried sludge and the effluent. The results of the mass balance are presented in Table 8.5.

It is interesting to note that on average, about 47% of the solids were retained in the dried layer of sludge, about 12% passed through the bed and were captured in the leachate (see below for a discussion on leachate) and 42% were 'unaccounted' for. The 'unaccountable' solids were lost due to a combination of mineralisation and/or sorbtion onto/integrated into the filter media. These results illustrate why media regeneration is necessary, and the importance of further treatment for the leachate treatment due to the high solids concentrations.

8.6.3 Feeding frequency and resting phase

Loading of PDBs is always intermittent and the frequency varies from site to site. Typically, loading occurs one to three times a week by means of valves and siphons or pumping devices installed in a buffer tank, which is preferable to loading directly from a truck. Once loaded with a layer of sludge, the bed is allowed to drain completely, during which time the pores of the filter matrix are emptied of leachate, and refilled with air. The next application of sludge effectively seals off these small pockets of air. Once this occurs, oxygen, which is instrumental in the nitrification process is rapidly depleted (Kadlec and Wallace, 2009). Therefore the resting time between loading periods is very important as it prevents biological clogging and allows pores to refill with oxygen (Stefanakis and Tsihrintzis, 2012a).

However, if the resting times between FS loading is increased, more PDBs would be required to treat the same volume of sludge. Using a semi-empirical equation, researchers determined that in order to maximise water-loss and minimise costs, 11 days was the optimum number of days between loadings (Giraldi and Iannelli, 2009). This is in keeping with other reported practices of between one and three weeks (Stefanakis and Tsihrintzis, 2012a).

Table 8.5 Total Solids (TS) mass balance of faecal sludge from septic tanks on planted drying beds after 300 days of operation (adapted from Koottatep and Surinkul *et al.*, 2004)

	Unit #1		Unit #2		Unit #3		Average
	(kg TS/m^2)	(%)	(kg TS/m^2)	(%)	(kg TS/m^2)	(%)	(%)
Faecal sludge	187		115		112		-
Dried sludge	93	50	60	52	43	38	47
Percolate	20	11	14	12	13	12	12
Unaccounted	74	39	41	36	56	50	42

8.6.4 Plant harvesting and regrowth

As mentioned in Section 8.5.2 a benefit of PDBs is that the macrophytes can be harvested for beneficial enduse (covered in more detail in Chapter 10). Macrophytes grown in PDBs generate two to three times the biomass that is produced in naturally occurring wetlands, due to the availability of nutrients, especially nitrogen and phosphorus (Warman and Termeer, 2005). Harvesting generally occurs on a regular basis (e.g. during desludging), but could also be dictated by other considerations such as the need to sell the plants for enduse purposes (e.g. fodder) or to mitigate insect attacks (Altieri and Nicholls, 2003; Pimental and Warneke, 1989). It has been found that insects can have a great impact on larger plants, especially in dense monocultures, which may require the removal of older plants to allow new and vigorous shoots to take over. *E. pyramidalis*, which is highly sought after as fodder in some regions, can be harvested up to three times a year (Kengne *et al.*, 2008).

Currently, harvesting is carried out manually since most of the PDBs have been operated at experimental or pilot scale. Mechanical methods will probably be introduced when PDBs are operated at full scale. Harvesting is done by cutting plants at the surface, not by pulling out the whole plant. This prevents damage to the filter, and if the rhizome is left intact, the leaves and stalks can readily regrow.

8.6.5 Bed emptying

Finding the optimum loading rate is important for the operation and maintenance of PDBs to ensure that the sludge layer does not accumulate and become too thick and require desludging before it is fully drained. On an experimental scale, it has been found that a loading rate of 100 kg TS/m^2/year, results in the accumulation of approximately 30 to 40 cm/year of sludge, compared to 50-70 cm/year if loading rate of 200 kg TS/m^2/year is used. For PDBs with a freeboard of 1.5 m to 2 m these loading rates would result in a 3-5 year operation life before desludging is required (Kengne *et al.*, 2011). Prior to removal, sludge can be left for several months without additional loading which results in greater pathogen and moisture reduction. For example, a significant increase of 25-43% in dry matter content was achieved when pilot-scale beds were left for one month prior to desludging in Cameroon, and the helminth (Ascaris) egg concentration was reduced to less than 4 viable eggs/g TS from 79 eggs/g TS and a viability 67% (Kengne *et al.*, 2009b).

Sludge removal is currently carried out manually, although mechanical desludging machines may be employed in the future. Depending on how carefully the bed was desludged, it may be necessary to reconstitute the substrate of the bed, either by adding to or replacing the upper layer (sand or fine gravel), or by replacing the entire bed.

8.6.6 Leachate

Leachate is the liquid that filters down through the sludge layer and the porous media. It should be collected and treated with a subsequent treatment technology prior to discharge to the environment. However, the leachate can also be used for irrigation or aquaculture (covered in more detail in Chapter 10). If the PDBs are located at a wastewater treatment plant, the leachate can be treated with the wastewater. Other possibilities include dedicated onsite technologies such as waste stabilisation ponds (Chapter 5; Strauss *et al.*, 1997). Measurement of the leachate characteristics over time shows that most parameters have a peak concentration following sludge loading (COD, PO_4^{3-}, TSS, VSS) followed by a rapid decline, indicating a flushing phenomenon and/or the dynamic treatment mechanisms at work in the bed. A study conducted with sludge from a biological wastewater treatment plant, showed an 80% reduction in COD (initially 2,500 mg/L) during the first 10 minutes after loading, and over 92% COD reduction after two days. Additionally, initial ammonium concentrations of more than 350 mg/L decreased rapidly and were reduced by 90% within the first 10 minutes after loading. This decrease in ammonia was accompanied by an increase in nitrate concentration, thereby reflecting the rapid nitrification process (Stefanakis and Tsihrintzis, 2012a). Research at AIT illustrated that approximately 12% of the total solids remain in the leachate (Table 8.5). The same research on parallel beds also showed that 45% of the total liquid in the loaded sludge ended up as leachate (while 5% remained in the sludge layer, and 50% was lost to evapotranspiration). Furthermore, the leachate was only found to contain about 5% of the total nitrogen applied, with the majority (82%) being taken up and a small percentage (13%) remaining in the sludge layer (Koottatep and Surinkul, 2004). In general, leachate stops draining from the bed one to two days after loading. Leachate production is highly variable; high shock loads and intermittent flows must be taken into consideration in the design of any subsequent treatment process.

8.6.7 Factors affecting performance

The main causes of poor operational performance include poorly constructed filters; inadequate capillary connections; an inadequate number of beds, insufficient bed area; or overloading during commissioning and subsequent operation (Nielson, 2005). Other factors such as the settling of particulate matter, fast-growing biofilm, chemical precipitation and salt formation, and dense root development have also been mentioned as further reasons for clogging (Molle *et al.*, 2006). Operational problems can be overcome by proper dimensioning of the PDBs which takes the dewatering potential of the sludge into account and does not rely solely on calculations of the sludge volume production. The loading program should be designed to prevent the sludge layer from accumulating too quickly as this can inhibit the growth of such that the macrophytes. Table 8.6 summarises suggested operational parameters for PDBs and the operational aspects that need to be taken into consideration.

8.7 COSTS AND BENEFITS

One of the most attractive features of PDBs compared to other sludge treatment technologies is the fact that they have low capital, operating, maintenance, supervision and energy costs (Stefanakis and Tsihrintzis, 2012a). PDBs do not require chemical flocculants, centrifuges or belt presses (Edwards *et al.*, 2001). However, PDBs can be more expensive than unplanted drying beds, both in terms of the capital costs (e.g. purchasing macrophytes), and operational costs (e.g. plant harvesting, weeding and vector control), but they have the advantage of requiring less desludging (e.g. once every few years versus every two to three weeks).

Table 8.6 Operational parameters for a planted drying bed

Treatment component	Details	Remarks
Loading	60-250 kg TS/m^2/year	Depending on the sludge source and conditions
Feeding frequency	1-3 times a week	Depending on the weather conditions, the dry matter content of the sludge and the plant species
Resting	2 days to several weeks	Depending on the weather conditions, the dry matter content of the sludge and the plant species
Plant acclimatisation	Start-up with plant density of 4-12 shoots/m^2 Apply domestic wastewater and gradually add FS until the plants achieve a height of 1 m	Start-up during a rainy or wet season is recommended
Plant harvesting	Up to 3 times/year, following a few years of operations or during desludging	Depending on plant type, the growth status and valorisation option. Valid especially for *Echinochloa pyramidalis*

A study in Italy, attempted to quantify the costs associated with building and operating a PDB for the treatment of wastewater sludge. Although the values obtained are not representative of costs worldwide, they do provide some useful insights. Construction costs, including the plants, other materials and labour were estimated to be in the region of 350 USD/m^2 while the operating costs, including plant harvesting, sludge transport and disposal were calculated to be 180 USD/m^2 (Giraldi and Iannelli, 2009). Considering a sludge production rate (from primary wastewater treatment) of 16kg TS/capita/year, and assuming loading rates between 30 and 75 kg TS/m^2/year these PDBs could treat the sludge of between 1.7 and 4 capita/m^2 (Stefanakis and Tsihrintzis, 2012a). Since a large portion of the operating costs are associated with transport (e.g. transport to the disposal site and transport of an endproduct from the site), local transport costs can significantly impact on the total. Furthermore, construction costs will vary depending on the availability and cost of local labour and materials (Giraldi and Iannelli, 2009).

8.8 EXAMPLE PROBLEM

In order to demonstrate the calculations that are required in designing and constructing a PDB, an exercise is presented below as a practical example. Table 8.7 provides information that can be used to assist with the required calculations.

8.8.1 Practice question

After conducting a preliminary study, a municipality would like to design a PDB to dewater FS having the following characteristics:

Estimated annual FS emptied: 5,000 m^3/year

Average TS content of raw FS: 30,000 mg/L (or 30 kg TS/m^3)

Using this information:

Determine the total solids of faecal sludge per year:

5,000 m^3/year x 30 kg TS/m^3: 150,000 kg TS/year

Determine the specific area required for the planted-sludge drying bed

Choose the TS loading rate: 200 kg TS/m^2/year

Area required: $150{,}000 \text{ kg TS/year} \times \dfrac{1}{200 \text{ kg TS/m}^2\text{/year}} = 750 \text{ m}^2$

This specific area can be divided into several beds according to the topography of the site. Assuming that the topography of the area is uniform, the specific area can be split into 5 beds of 150 m^2 each Additional areas for bar screen, mixing tanks, leachate tanks and vacuum trucks need to be taken into consideration. The minimum area is about 20% of specific area.

Table 8.7 Suggested design parameters of planted sludge drying beds for faecal sludge dewatering

Design parameter	Suggested ranges	Unit
FS production rate	1.5	L/capita/day
TS content	30	mg/L
Solid loading rate	200	kg TS/m^2/year
FS application frequency	1 to 2	times/week

8.9 CONCLUSIONS AND RECOMMENDATIONS

PDBs are a relatively new technology for treating FS from septic tanks and other onsite sanitation technologies in low- and middle-income countries. Extensive experience in Europe and the US has produced robust results, but the data are not entirely applicable to FS due to the sludge type and strength, and the climatic conditions. Currently, many experimental and pilot scale beds are being investigated in various parts of the world, especially tropical climates where solar radiation and evapotranspiration is high. PDBs have long been known as a reliable technology for sludge treatment, but have become increasingly attractive for FSM in rapidly growing cities in low- to middle-income countries as they are less costly to build than conventional wastewater sludge treatment technologies, can be built using local materials and labour, and require little maintenance, few to no chemicals and minimal energy to operate successfully. Although the macrophytes require some time to acclimatise to the nutrient-rich sludge, the PDB can then operate for up to 10 years without desludging and the macrophytes can be harvested for beneficial use. The stabilised sludge layer can also be used as a soil amendment and organic fertiliser.

However, PDBs require a significant amount of space (0.25 to one m^2/capita) and therefore, the technology is not well-suited to dense, urban areas. Furthermore, the bed must be accessible by trucks that transport sludge, and should therefore be built on or near roads that are easily traversed by large vehicles. Although resilient, macrophytes may be prone to insect attacks and parasitism. Therefore, although maintenance is not constant, it must be diligent. In recent years, much research has been carried out in order to determine optimum parameters for the design and operation of the most robust PDBs as possible. There are, however still questions that remain unanswered, such as:

- the effects of feeding frequency on bed performance;
- the vulnerability and resilience of macrophytes to insect attacks;
- the effects of high conductivity and ammonia;
- the most effective treatment methods for leachate;
- the long-term (10+ year) performance of the beds; and
- the cost-benefit analysis of the system.

Each of these aspects should be researched under different loading rates, with different types of FS and under different climactic conditions. Although research remains important, priority should be given to upscaling and promoting PDBs whenever possible and appropriate. Time must not be wasted on perfecting this technology, but rather building on current knowledge and disseminating evidence as it is gathered.

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End of Chapter Study Questions

1. Describe the main components of PDBs, and the basic fundamentals of their operation.
2. Explain what macrophytes are, and list four essential roles they play in FSM.
3. Identify four performance indicators that are important for monitoring the performance of PDBs to ensure they are meeting treatment objectives.
4. Finding the optimum loading rate is important for the operation and maintenance of PDBs, explain why this is important.
5. What are challenges and benefits of using the PDB technology for FSM in dense urban areas?