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## Review Paper

### Planted drying beds in the African context: state of knowledge and prospects

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#### ABSTRACT

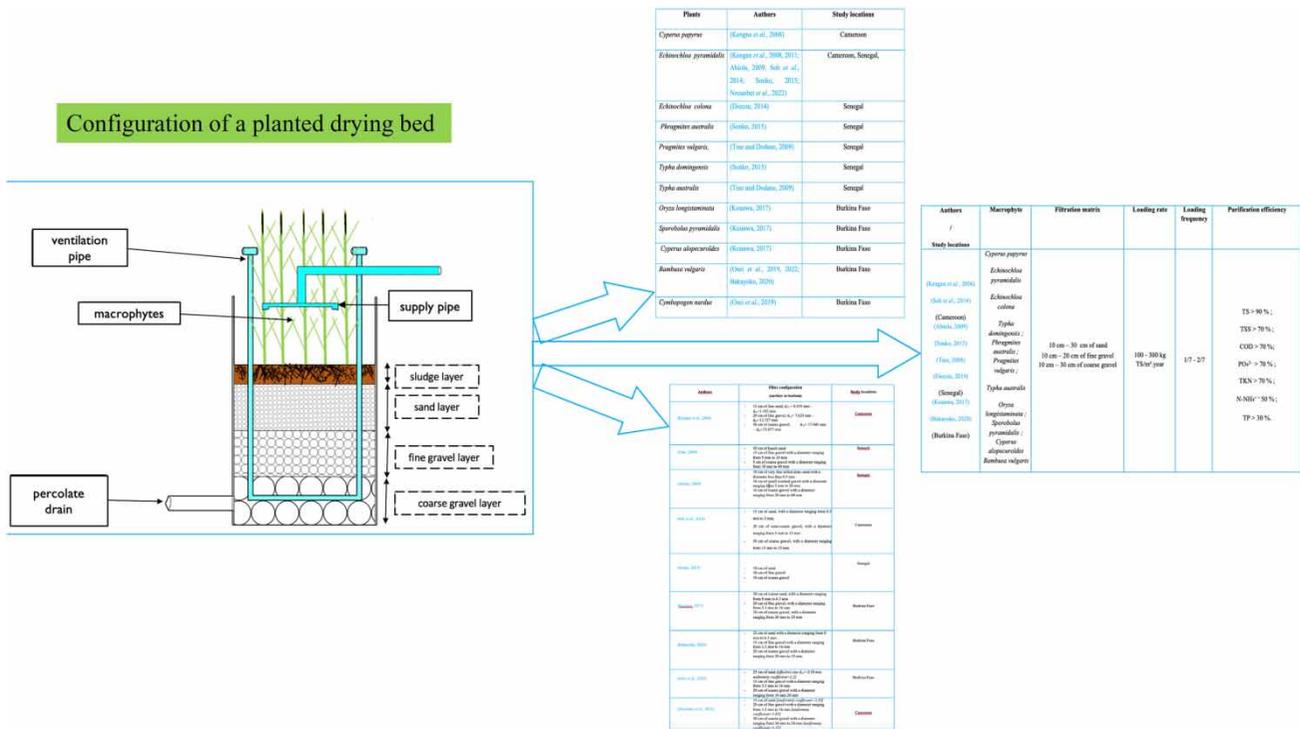
In low-income countries, the discharge of untreated fecal sludge directly into the environment is a common practice that poses a threat to both environmental and public health. Planted drying beds (PDBs) are a promising and low-cost option for treating fecal sludge. Therefore, in Africa, the use of PDBs for treating fecal sludge is increasingly valuable due to the technology's high efficiency, especially in tropical climates. This paper presents a literature review on the use of PDBs for treating fecal sludge in Africa, focusing on current research requirements and directions. This review shows that *Echinochloa pyramidalis* appears to be the most effective indigenous species used for this purpose, while also highlighting the lack of stability in the design and implementation models of PDBs. Standardizing and generalizing implementation methodologies for PDBs in Africa, researching new native and efficient species, and testing combinations of different species in the beds would all be beneficial.

**Key words:** *Echinochloa pyramidalis*, fecal sludge, planted drying beds, pollutant removal efficiencies

#### HIGHLIGHTS

- *Echinochloa pyramidalis* has emerged as the most effective indigenous species used in the African context.
- It is recommended to prioritize the identification of new native species that exhibit high efficacy for future research.
- The current use of planted drying beds for fecal sludge treatment does not allow for direct disposal of percolates in the environment.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Although high rates of open defecation initially marked most African countries' sanitation situations, multiple initiatives since the 2000s have reduced the severity of this problem and enabled the establishment of onsite sanitation systems. Because more than 55% of dwellings are not connected to a sewage system, onsite sanitation is usual (Ingallinella et al. 2002; Laminou Manzo et al. 2015; Nansubuga et al. 2016; Abubakar 2017). The management of sludge from these facilities, however, poses a new difficulty. The implementation of a system for emptying, transporting, and evacuating this sludge in a way to minimize population health hazards while still respecting the environment is still an issue. Fecal sludges (FSs) are dumped in nature on the outskirts of cities by emptying companies without being treated, exposing all the health and environmental dangers that this practice entails (Nansubuga et al. 2016; Bishoge 2021).

Most African countries currently face FS evacuation and management issues. Firstly because of the lack of logistics and the required organization to manage the large amounts of sludge produced, and secondly, the socio-economic context not allowing the use of the same technologies as in developed countries. Moreover, sludge management requires specialized technical understanding (Uggetti et al. 2010). Sludge treatment operations mainly involve two processes, namely (i) dewatering and (ii) stabilization (Kadlec & Knight 1996).

The goal of the dewatering process is to minimize sludge volume while increasing total solid matter (TSM) content in the finished sludge to save operating expenses. On the other hand, sludge stabilization tries to keep the biodegradable fraction of organic matter in the sludge stable by lowering the organic percentage of volatile matter (VM). Several sludge treatment technologies are based on these two unitary operations, i.e., sludge dewatering and stabilization. One of them, which is of major interest, is the planted drying bed (PDB). This technology is increasingly finding its place in the African context and deserves special attention. This literature review aims to discuss the current state of the use of PDBs in the treatment of FS in Africa, as well as additional research needs and perspectives. It is noted that in the scientific literature, there is no recent technical document that provides an update on the progress of this technology in Africa. Therefore, this work can serve as a summary of the different practices and techniques currently used in the field of PDBs for the treatment of FS. The next paragraphs will address the implementation and operation aspects of PDBs in Africa, the achieved treatment performance, observed challenges, and recommendations for future research in the field.

## 2. GENERAL INFORMATION ON DRYING BEDS

### 2.1. PDBs in the world

PDBs were invented in Europe in the 1980s to solve the inefficiency and clogging issues that plagued unplanted drying beds (Bittmann & Seidel 1967). This approach was developed by German researchers who decided to plant reeds (*Phragmites australis*) on unplanted drying beds to avoid clogging and the need for cleaning after each sludge feeding (Bittmann & Seidel 1967). The goal was to use the stem–rhizome–root system created by plants in the sludge layer to create water flow preferential channels. The technique was quickly embraced and applied in the 1990s in Germany (Hofmann 1990), Denmark (Nielsen 1990; Nielsen 2005), the United States (Kim & Cardenas 1990; Burgoon *et al.* 1997; Kim & Smith 1997), and France (Lesavre & Iwema 2002; Liénard *et al.* 2006; Troesch 2009; Vincent 2011) for activated sludge treatment. In the late 1990s and early 2000s, countries like Belgium (De Maeseneer 1997), the United Kingdom (Edwards *et al.* 2001), Poland (Hardej & Ozimek 2002; Obarska-Pempkowiak *et al.* 2003), Italy (Giraldi *et al.* 2009), Spain (Uggetti *et al.* 2009), and those in the South, where climatic conditions are more conducive to the usage of this technology, began to adopt it.

PDBs were initially developed to dewater and stabilize sludge from small activated sludge treatment plants in Europe and the United States (Kadlec & Knight 1996; Liénard & Payrastré 1996; Nielsen 2003). The process was then successfully adapted in other parts of the world for different types of sludge, including household FS.

### 2.2. PDBs in Africa

PDBs are appropriate for tropical regions because seasonal climate fluctuations are minor and solar radiation is constant. Indeed, according to Edwards *et al.* (2001), in temperate climates, the performance of PDBs is better in summer when there is more sunlight than in winter (Kivaisi 2001; Nielsen 2005; Liénard *et al.* 2008; Dan *et al.* 2011). The use of PDBs in Africa dates back to 2005–2006, when authors such as Kengne *et al.* (2006), in partnership with the Swiss Federal Institute of Aquatic Science and Technology (Eawag), made some experimentations on the process. Kengne's research focused on selecting local macrophyte species (*Echinochloa pyramidalis* and *Cyperus papyrus*) as well as improving the system's treatment performance. Most PDB experiments in Africa were conducted on a pilot scale. This was the case for the experimentations conducted in Cameroon (Kengne *et al.* 2006, 2008, 2011; Ngoutane *et al.* 2012; Soh *et al.* 2014). However, several authors have conducted large-scale deployments in Senegal (Abiola 2009; Tine & Dodane 2009). Another example of large-scale implementation is the 'Cambérène' treatment plant in Dakar (Dodane *et al.* 2012). Some recent research was also conducted in Burkina Faso at the 'International Institute for Water and Environmental Engineering (2iE)'. A pilot scale evaluation of the performance of indigenous species in PDBs has been done. In Benin, projects for the construction of sewage sludge treatment plants using PDBs are in progress.

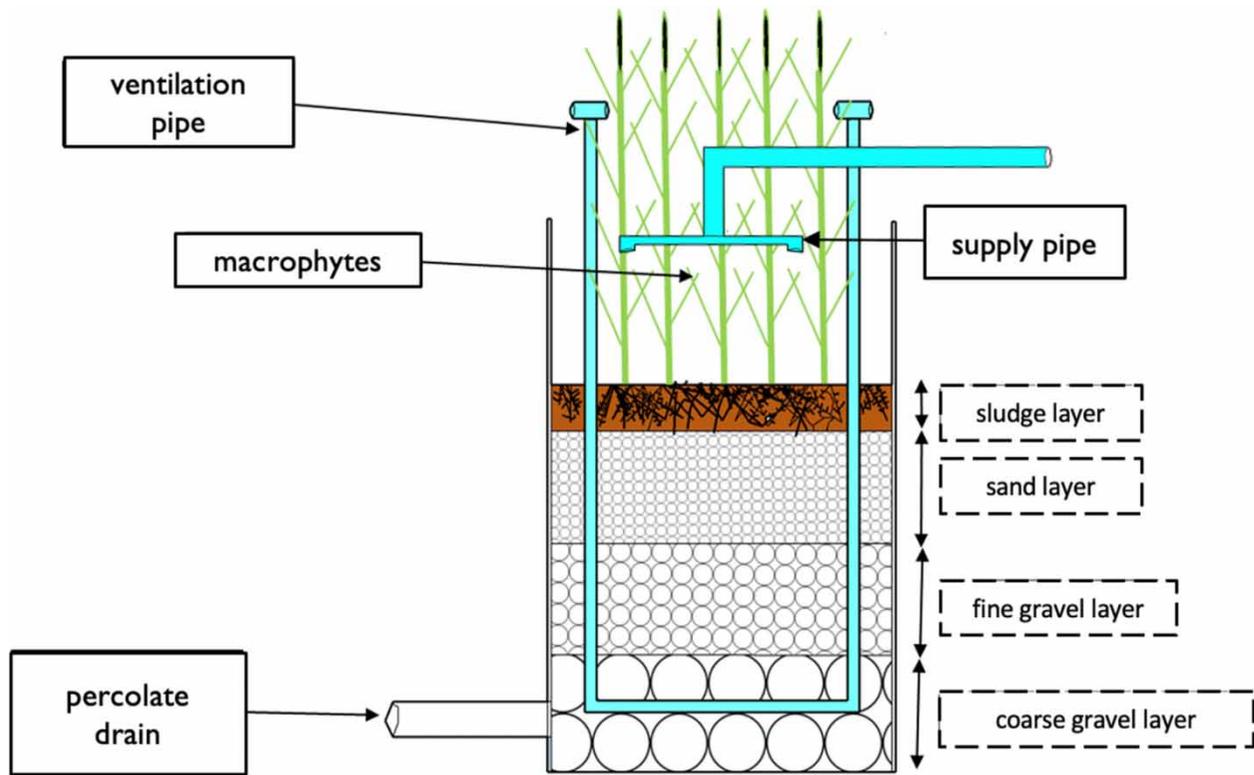
## 3. DESIGN AND IMPLEMENTATION OF PDBS

As depicted in Figure 1, a PDB typically consists of a vegetated granular bed, a distribution system, and a drainage outlet. The type of plant material used, the footing densities of the retained macrophyte, the type of substrates used, the layering configuration of the materials used, and the feeding regime all affect treatment efficiency.

The feeding of sludge to the beds is commonly done by batch system intermittently (Kouawa 2017) with heights up to 20 cm (Kadlec & Wallace 2008) or even 30 cm in some circumstances. Still, the preference is more evident for heights of 20 cm (Dodane & Mariska 2014). Due to the varying impacts of different sludge heights (obtained after feedings), which depend on the quality of this sludge, the reasoning based on applied loads expressed in kg TS/m<sup>2</sup>/year is more appropriate. Concerning the type of feeding, the batch feeding system is the most commonly used and recommended (Molle 2003). The pollutants in the sludge are subsequently removed using a combination of physical, chemical, and biological processes that result in the sludge getting dewatered, stabilized, and mineralized. Plants, microorganisms, and other physical variables play a role in biological treatment procedures in which various biochemical changes occur (Kootatép *et al.* 2005).

### 3.1. Plant material

Several studies have revealed the increased use of plants in PDBs (Edwards *et al.* 2001; Stefanakis & Tsihrintzis 2012). Plants introduced in PDBs improve the sludge dewatering process and remove organic pollutants that act as nutrients due to their evapotranspiring properties and root network. Furthermore, the presence of roots encourages the expansion of microorganisms engaged in pollution elimination. Common reeds of the genus *Phragmites* sp. (Puigagut *et al.* 2007) and cattails of the genus *Typha* sp. are the most commonly used species in applying this technology (Stefanakis *et al.* 2014). In Africa, the



**Figure 1** | Typical configuration of a PDB.

dynamic is much more oriented toward promoting endogenous species (*C. papyrus*, *E. pyramidalis*, *Echinochloa colona*, *P. australis*, *Phragmites vulgaris*, *Typha domingensis*, *Typha australis*, *Oryza longistaminata*, *Sporobolus pyramidalis*, and *Cyperus alopecuroides*, *Bambusa vulgaris*) (Table 1). Some species, such as the fodder plant *E. pyramidalis* (Kengne *et al.* 2006; Abiola 2009), and others, such as the bamboo species *B. vulgaris* (Bakayoko 2020), are highly efficient and give good results. The literature also revealed that the species *O. longistaminata*, *S. pyramidalis*, and *C. alopecuroides* are not suitable for use in PDBs because all three species' plants withered and died (Kouawa 2017).

**Table 1** | Some plants used in PDBs in Africa

Plants	Authors	Study locations
<i>Cyperus papyrus</i>	Kengne <i>et al.</i> (2008)	Cameroon
<i>Echinochloa pyramidalis</i>	Kengne <i>et al.</i> (2008, 2011), Abiola (2009), Soh <i>et al.</i> (2014), Sonko (2015), Nzouebet <i>et al.</i> (2022)	Cameroon, Senegal
<i>Echinochloa colona</i>	Diocou (2014)	Senegal
<i>Phragmites australis</i>	Sonko (2015)	Senegal
<i>Pragmites vulgaris</i>	Tine & Dodane (2009)	Senegal
<i>Typha domingensis</i>	Sonko (2015)	Senegal
<i>Typha australis</i>	Tine & Dodane (2009)	Senegal
<i>Oryza longistaminata</i>	Kouawa (2017)	Burkina Faso
<i>Sporobolus pyramidalis</i>	Kouawa (2017)	Burkina Faso
<i>Cyperus alopecuroides</i>	Kouawa (2017)	Burkina Faso
<i>Bambusa vulgaris</i>	Osei <i>et al.</i> (2019, 2022), Bakayoko (2020)	Burkina Faso
<i>Cymbopogon nardus</i>	Osei <i>et al.</i> (2019)	Burkina Faso

The *E. pyramidalis* plant is currently the most effective in Africa. Purification yields were highest in beds with this plant: 97% for DM; 99% for total suspended solids (TSS); 99% for chemical oxygen demand (COD); 91% for  $\text{NH}_4^+$  and 97% for  $\text{PO}_4^{3-}$  (Abiola 2009). In PDBs, *E. pyramidalis* has a significant rate of growth and multiplication. Some researchers noted that after one month, concentrations of over 100 individuals/ $\text{m}^2$  could be achieved (Kengne *et al.* 2006). Its capabilities enable this plant to quickly colonize the bed's surface and build a root and stem network that cracks the sludge layers (Abiola 2009), enhancing the system's hydraulic performance, aeration of the upper layers through these fissures, and oxygen release from the roots. *E. pyramidalis* is also a robust plant, able to tolerate the water stress that is common in PDBs, as well as the high fluctuations in pollutant load, particularly salinity rate, which can be harmful to other plants very quickly (Kouawa 2017).

Comparative tests of *Phragmites* sp. and cattails of the genus *Typha* sp. for the treatment of agri-food sludge demonstrate that *Phragmites* sp. has a higher evapotranspiration (ET) rate (Wang *et al.* 2009). Furthermore, under tropical conditions, comparison tests between *E. pyramidalis*, *P. australis*, and *T. domingensis* reveal that *E. pyramidalis* has the best ET rates, with percolate percentages of 34, 38, and 47%, respectively, indicating that *E. pyramidalis* has the best ET rates (Sonko 2015). Comparative studies by Dodane *et al.* (2011) on *E. pyramidalis*, *T. australis*, and *P. vulgaris* also clearly highlighted the robustness of *E. pyramidalis* compared to the other two.

It should be mentioned, however, that other *Echinochloa* species, such as *Echinochloa callopus* and *Echinochloa staghmina*, may be more effective than *E. pyramidalis*. Still, no comparative research has been done on them. In addition to *E. pyramidalis*, Gueye *et al.* (2016) found that *Echinochloa crus-galli*, *Paspalidium geminatum*, and *Paspalum vaginatum* are all suitable candidates for FS treatment. However, compared to the other plants available, *E. pyramidalis* is still the finest, considering its numerous advantages (size, density of the root network, robustness). At a certain stage of the system's evolution, it becomes necessary to mow down the plants. Plant harvesting from PDBs refers to the process of removing and harvesting plants that have been grown in drying beds as part of a treatment system for sludge.

The harvested plants are typically removed from the beds once they have reached maturity, and they can be disposed of or used for various purposes. Depending on the type of plants used, they may be composted, used for bioenergy production, or even consumed as a food source (Gueye *et al.* 2016). Mowing down the plants is generally carried out during the cleaning of the beds, but it can be performed at other times as needed. For example, it is necessary to mow down the plants during insect attacks to allow young and more vigorous plants to take over. This activity is still done manually, but mechanized equipment is necessary for large stations. Plant harvesting should be done by cutting the plants at the surface of the beds without uprooting them. This avoids damaging the filtration matrix and allows the remaining rhizomes to continue functioning.

Plant harvesting from PDBs is an important aspect of the overall management of these systems, as it helps to maintain their effectiveness and prevent the buildup of excess biomass that can hinder treatment performance. It also provides an opportunity to recover valuable resources and reduce waste. Moreover, some authors have demonstrated that multiple harvests of plants increase biomass production (to be harvested and commercialized) and system processing performance (Rozema *et al.* 2016).

### 3.2. Granular medium

PDBs consist of several layers of granular media of increasing size from top to bottom, through which water percolates. The beds are typically composed of three layers (Table 2). The topmost layer is in contact with the mud and is typically made up of sand. Below the surface layer is a transition layer, which is usually composed of fine gravel. Finally, at the bottom of the bed is a layer of coarse gravel.

The top layer of the filter is common sand or fine gravel, with a uniformity coefficient larger than 3.5, to prevent hydraulic failure and clogging of the system. The total height of the layers varies from 30 to 90 cm (Paing & Voisin 2005; Abiola 2009), and the thickness of each layer, as well as the qualities of the material in each layer, varies from one author to the next. Some authors investigated the use of compost in place of sand and reported that compost increases rapid plant development during the acclimation period but decreases the quality of the leachate (Troesch 2009).

Aeration drains can be inserted between the layers to optimize the filter matrix's functionality. Comparative investigations of these aeration drains demonstrate that while their presence does not directly correlate with dewatering effectiveness, it maximizes plant and bacterial flora growth, resulting in better ET (Stefanakis & Tsihrintzis 2012). Authors usually used three layers of a granular medium.

**Table 2** | Examples of PDB configurations adopted in Africa

Authors	Filter configuration (surface to bottom)	Study locations
Kengne <i>et al.</i> (2006)	<ul style="list-style-type: none"> <li>- 15 cm of fine sand; <math>d_{10} = 0.333</math> mm–<math>d_{60} = 1.182</math> mm</li> <li>- 20 cm of fine gravel; <math>d_{10} = 7.625</math> mm–<math>d_{60} = 12.727</math> mm</li> <li>- 30 cm of coarse gravel; <math>d_{10} = 17.045</math> mm–<math>d_{60} = 23.077</math> mm</li> </ul>	Cameroon
Tine (2009)	<ul style="list-style-type: none"> <li>- 30 cm of beach sand</li> <li>- 15 cm of fine gravel with a diameter ranging from 5 to 10 mm</li> <li>- 5 cm of coarse gravel with a diameter ranging from 10 to 40 mm</li> </ul>	Senegal
Abiola (2009)	<ul style="list-style-type: none"> <li>- 10 cm of very fine rolled dune sand with a diameter less than 0.5 mm</li> <li>- 10 cm of small-crushed gravel with a diameter ranging from 5 to 20 mm</li> <li>- 10 cm of coarse gravel with a diameter ranging from 20 to 60 mm</li> </ul>	Senegal
Soh <i>et al.</i> (2014)	<ul style="list-style-type: none"> <li>- 15 cm of sand, with a diameter ranging from 0.3 to 2 mm,</li> <li>- 20 cm of semi-coarse gravel, with a diameter ranging from 5 to 15 mm</li> <li>- 30 cm of coarse gravel, with a diameter ranging from 15 to 25 mm</li> </ul>	Cameroon
Sonko (2015)	<ul style="list-style-type: none"> <li>- 10 cm of sand</li> <li>- 10 cm of fine gravel</li> <li>- 10 cm of coarse gravel</li> </ul>	Senegal
Kouawa (2017)	<ul style="list-style-type: none"> <li>- 20 cm of coarse sand, with a diameter ranging from 0 to 6.3 mm</li> <li>- 20 cm of fine gravel, with a diameter ranging from 3.3 to 16 mm</li> <li>- 20 cm of coarse gravel, with a diameter ranging from 20 to 25 mm</li> </ul>	Burkina Faso
Bakayoko (2020)	<ul style="list-style-type: none"> <li>- 25 cm of sand with a diameter ranging from 0 to 6.3 mm</li> <li>- 15 cm of fine gravel with a diameter ranging from 3.3 to 16 mm</li> <li>- 20 cm of coarse gravel with a diameter ranging from 20 to 25 mm</li> </ul>	Burkina Faso
Osei <i>et al.</i> (2022)	<ul style="list-style-type: none"> <li>- 25 cm of sand [effective size <math>d_{10} = 0.28</math> mm; uniformity coefficient = 2.2]</li> <li>- 15 cm of fine gravel with a diameter ranging from 3.3 to 16 mm</li> <li>- 20 cm of coarse gravel with a diameter ranging from 10 to 20 mm</li> </ul>	Burkina Faso
Nzouebet <i>et al.</i> (2022)	<ul style="list-style-type: none"> <li>- 15 cm of sand [uniformity coefficient = 3.55]</li> <li>- 20 cm of fine gravel with a diameter ranging from 3.3 to 16 mm [uniformity coefficient = 1.67]</li> <li>- 30 cm of coarse gravel with a diameter ranging from 10 to 20 mm [uniformity coefficient = 1.37]</li> </ul>	Cameroon

While layer heights do not appear to substantially impact treatment efficiency, the particle size characteristics of the granular material that makes up each layer do (Stefanakis & Tsihrintzis 2012). Indeed, the greater the quality of the leachate, the smaller the particle size of the surface layer material; however, the risk of clogging also increases. This is the case of Abiola (2009), who used a very fine rolled dune sand of 0.5 mm as a surface layer and achieved one of the best purification results in the African context (Table 3). However, in West Africa, climatic conditions cause large ET rates, which significantly minimize the risk of clogging.

### 3.3. Feeding cycles

PDBs go through a feeding and resting cycle. These cycles can last from a few days to several weeks (Koottatep *et al.* 2005). The sludge is usually dumped on the bed's surface during feeding. Surface load calculated in the quantity of dry matter brought on a bed per unit of surface in one year (or kg TS/m<sup>2</sup>/year) is used to estimate the amount of sludge to be brought during the PDB's sludge feeding.

Breaking the volumes associated with retained loads into short cycles is more advantageous than using long cycles (faster dehydration of sludge) (Nielsen 2005). However, according to published research, the best time between feeds for high drying

**Table 3** | An overview of PDBs experimentations in Africa

Authors/Study locations	Macrophyte	Filtration matrix	Loading rate	Loading frequency	Purification efficiency
Kengne <i>et al.</i> (2006) (Cameroon)	<i>Cyperus papyrus</i> <i>Echinochloa pyramidalis</i>	<ul style="list-style-type: none"> <li>- 15 cm of fine sand; <math>d_{10} = 0.333</math> mm-<math>d_{60} = 1.182</math> mm</li> <li>- 20 cm of fine gravel; <math>d_{10} = 7.625</math> mm-<math>d_{60} = 12.727</math> mm</li> <li>- 30 cm of coarse gravel; <math>d_{10} = 17.045</math> mm- <math>d_{60} = 23.077</math> mm</li> </ul>	100, 200, and 300 kg TS/m <sup>2</sup> .year	1-2 days/5-6 days	For 100 kg TS/m <sup>2</sup> .year: (95.2-99.9%) TSS; (47.4-98.7%) TS; (96.7-99.9%) COD; (77.8-99.6%) TKN; (44.2-99.8%) NH <sub>4</sub> <sup>+</sup> For 200 kg TS/m <sup>2</sup> .year: (78.5-99.9%) TSS; (74.4-99.8%) TS; (73.4-99.9%) COD; (69.2-99.3%) TKN; (50.0-99.9%) NH <sub>4</sub> <sup>+</sup> For 300 kg TSS/m <sup>2</sup> .year: (61.8-99.9%) TSS; (62.6-99.9%) TS; (78.0-99.9%) COD; (78.7-98.3%) TKN; (32.8-99.9%) NH <sub>4</sub> <sup>+</sup>
Abiola (2009) (Senegal)	<i>Echinochloa pyramidalis</i>	<ul style="list-style-type: none"> <li>- 10 cm of very fine rolled dune sand with a diameter less than 0.5 mm</li> <li>- 10 cm of small-crushed gravel with a diameter ranging from 5 to 20 mm</li> <li>- 10 cm of coarse gravel with a diameter ranging from 20 to 60 mm</li> </ul>	283 kg of TS/m <sup>2</sup> .year		97%TS; 99%TSS; 100%VSS; 99% COD; 91% N-NH <sub>4</sub> <sup>+</sup> ; 97% PO <sub>4</sub> <sup>3-</sup>
Diocou (2014) (Senegal)	<i>Echinochloa colona</i>	<ul style="list-style-type: none"> <li>- 15 cm of coarse sand, with a diameter ranging from 0.09 to 8 mm</li> <li>- 10 cm of fine gravel, with a diameter ranging from 5 to 10 mm</li> <li>- 10 cm of coarse gravel, with a diameter ranging from 10 to 40 mm</li> </ul>	100, 200, and 300 kg TS/m <sup>2</sup> .year	3 days/7 days	90-94% TS; 17-24% TKN; 100% TSS; 64-99% COD;
Soh <i>et al.</i> (2014) (Cameroon)	<i>Echinochloa pyramidalis</i>	<ul style="list-style-type: none"> <li>- 15 cm of sand, with a diameter ranging from 0.3 to 2 mm</li> <li>- 20 cm of semi-coarse gravel, with a diameter ranging from 5 to 15 mm</li> <li>- 30 cm of coarse gravel, with a diameter ranging from 15 to 25 mm</li> </ul>	200 kg TS/m <sup>2</sup> .year	1 day/7 days	COD, BOD <sub>5</sub> , N-NH <sub>4</sub> <sup>+</sup> , TKN, PO <sub>4</sub> <sup>3-</sup> > 80%

(Continued.)

Table 3 | Continued

Authors/Study locations	Macrophyte	Filtration matrix	Loading rate	Loading frequency	Purification efficiency
Sonko (2015) (Senegal)	<i>Echinochloa pyramidalis</i> ; <i>Typha domingensis</i> ; <i>Phragmites australis</i> ;	- 10 cm of sand - 10 cm of fine gravel - 10 cm of coarse gravel	200 kg TS/ m <sup>2</sup> .year	1 day/7 days; 2 days/7 days; 3 days/7 days	TS, TSS and COD > 90%
Tine (2009) (Senegal)	<i>Phragmites vulgaris</i> ; <i>Typha australis</i>	- 30 cm of beach sand - 15 cm of fine gravel with a diameter ranging from 5 to 10 mm - 5 cm of coarse gravel with a diameter ranging from 10 to 40 mm	200 kg of TS/ m <sup>2</sup> .year	2 days/7 days; 3 days/7 days	-
Kouawa (2017) (Burkina Faso)	<i>Oryza longistaminata</i> ; <i>Sporobolus pyramidalis</i> ; <i>Cyperus alopecuroïdes</i>	- 20 cm of coarse sand, with a diameter ranging from 0 to 6.3 mm - 20 cm of fine gravel, with a diameter ranging from 3.3 to 16 mm - 20 cm of coarse gravel, with a diameter ranging from 20 to 25 mm	150 kg TS/ m <sup>2</sup> .year	1 day/7 days; 2 days/7 days	TSS > 85% ; COD 35–74% ; TP 21–73%.
Bakayoko (2020) (Burkina Faso)	<i>Bambusa vulgaris</i>	- 25 cm of sand with a diameter ranging from 0 to 6.3 mm - 15 cm of fine gravel with a diameter ranging from 3.3 to 16 mm - 20 cm of coarse gravel with a diameter ranging from 20 to 25 mm	155.6 kgTS/ m <sup>2</sup> .year ; 233.3 kgTS/ m <sup>2</sup> .year	-	-

performance with a small number of beds is 11 days (Giraldi *et al.* 2009). The climatic environment of West African countries maximizes drying efficiency. As a result, these countries have shorter resting durations than countries with temperate climates for an equal amount of dry matter. In general, feeding cycles (number of feedings/total number of days in the cycle) in Africa vary around 3/7, 2/7, 1/7 (Kouawa 2017), and 1/15 (Abiola 2009; Kengne *et al.* 2009) (Table 3).

#### 4. PDBS PURIFICATION EFFICIENCY

The climatic setting of West African countries, with a hot and dry propensity, makes them appropriate places for PDB implementation. The substantial association between climate and ET has been underlined in European studies (Stefanakis & Tsihrintzis 2011; Stefanakis *et al.* 2014). According to Giraldi *et al.* (2009), who also tested PDBs in Europe, summer results in a 40% improvement in dehydration performance. Water percolation due to gravity and ET due to climate are the two main mechanisms for sludge dewatering.

However, some African countries' hot and dry climates allow engineers to maximize ET and, as a result, sludge dehydration. On the other hand, the authors found that aeration drains put in PDBs have no significant effect on boosting sludge dewatering. However, the oxygen supply promotes the development of microbial degradation processes in the filter bed, resulting in improved leachate quality (Stefanakis & Tsihrintzis 2012).

While percolation and ET are the keys mechanisms for dewatering (Cofie *et al.* 2006), sludge stabilization and mineralization are facilitated by aerobic bacteria adhered to the granular support and the roots of planted macrophytes' rhizomes (Bialowiec *et al.* 2012; Gagnon *et al.* 2013; Brix 2017)

The fluctuation of loads affects the turbidity of the leachate and its physicochemical quality, according to many studies (Kengne *et al.* 2006; Vincent 2011). As a result, the higher the pollutant load, the higher the turbidity of the leachate. Kengne *et al.* (2006) and Vincent (2011) evaluated the effects of three loads on the performance of PDBs and found a positive correlation between loads and TSS and COD concentrations. However, the performance of PDBs in terms of purification remained superior to that of non-PDBs (Edwards *et al.* 2001). Indeed, Kengne *et al.* (2011) found average purification efficiencies of 95.8, 92.0, 95.4, 77.6, and 98.7% for TSS, total solids (TS), volatile solids (VS),  $\text{NH}_4^+$ , and COD removal, respectively. Abiola (2009) achieved average purification efficiency of 97% for TS, 99% for TSS, 100% for TSS, 99% for COD, 91% for  $\text{NH}_4^+$ , and 97% for  $\text{PO}_4^{3-}$ , which is one of the most evocative cases. Despite these excellent results, direct disposal of leachate into nature is not suggested because of the high contaminants. The concentrations of leachate are often higher than the effluent discharge regulations in nature. Treatment options include lagoons or treatment at a second leachate PDB, as well as recirculation, which can be a more or less effective technique for improving leachate quality.

However, some researchers found that the leachate still has high coliform concentrations even with adding additional PDBs (Soh *et al.* 2014). The authors' treatment scheme achieved compliance with WHO guideline thresholds for discharge or nonrestricted agricultural reuse at loading rates of 50, 100, and 150 mm/d for all monitored parameters, with the exception of nitrogen and fecal bioindicators. Studies have shown that treating FS in PDBs reduces helminth egg concentrations from a range of 600 to 6,000 helminth eggs/L of sludge to 170 eggs/g of dry matter (Ingallinella *et al.* 2002). In Africa, research shows that PDBs allow for the retention of helminth eggs in accumulated sludge and total absence in leachate (Kengne *et al.* 2009). In their study, Nzouebet *et al.* (2022) demonstrated that treatment with PDBs can lead to helminth egg elimination performance ranging from 82 to 100%.

## 5. FUTURE DIRECTIONS AND RECOMMENDATIONS FOR RESEARCH

PDBs have progressed well since their inception in Africa, but the growth of this technology has been far more empirical. There are still a lot of questions that need to be answered. The impact of variables such as water stress, salinity levels, climate (heat or cold tolerance), and illnesses (parasitic resistance) on plants like *E. pyramidalis*, which is now one of the most important species planted in Africa's drying beds, must be thoroughly investigated. This will help us understand the variables responsible for the plants' mortality or wilting rates. The research should also focus on identifying new species that can be more powerful than those presently known, such as *E. callopus* and *E. staghmina*, or *Panicum maximum*, *Echinochloa colona*, *E. crus-galli*, *Eleusine indica*, *Imperata cylindrical*, *P. geminatum* and *P. vaginatum* which may be more effective than *E. pyramidalis* (Gueye *et al.* 2016). Research should continue to discover new and higher-performing native species and test the efficiency of various plant combination designs in the beds. *Acrostichum aureum*, for instance, has previously demonstrated its effectiveness in treating wastewater with high salinity levels, as is the case with sewage sludge (Sansanayuth *et al.* 1996). It is a species that not only thrives in mangroves but also in freshwater settings and salt marshes. It's a fast-growing, hardy plant (Akinwumi *et al.* 2022). This plant has also demonstrated significant phytoaccumulation performance in recent studies (Nguyen *et al.* 2021). Furthermore, species like *Sesbania rostrata* can be a strong choice for PDBs, due to their ability to withstand periods of both soil waterlogging and drought, as well as their capacity to tolerate high levels of salinity (Ramani *et al.* 1989; Naher *et al.* 2020).

From the standpoint of purification performance, it would be possible to achieve improved purification performances by including the parameter of leachate residence time at the bottom of the beds before evacuation in the design and dimensioning parameters of the PDBs. It would be helpful to focus research on this direction. Some authors are already conducting studies in this direction by testing combinations of PDBs in series (Soh *et al.* 2014) or by combining PDBs with maturation ponds in order to refine the treatment of leachates (Soh *et al.* 2022). In the same dynamic and with the aim of improving the quality of percolates, the combination of PDBs with wastewater treatment processes such as the use of floating macrophytes

(Mahunon *et al.* 2018; Akowanou *et al.* 2023), microalgae (Liady *et al.* 2022), or activated carbon (Daouda *et al.* 2021) would be a promising research avenue.

## 6. CONCLUSION

The implementation of PDBs in Africa has made significant progress since their introduction to African sanitation. Among the various solutions adopted by Africa, particularly in sanitation, PDBs for the treatment of FS have proven to be an excellent alternative to conventional approaches. Therefore, they deserve the attention of the scientific community and leaders. However, there is still much room for improvement, especially regarding scaling up and adequate sizing considerations, taking into account population growth over time.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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