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Reed Beds for Sludge Dewatering and Stabilization

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Abstract

In urban and peri-urban areas of developing countries decentralized wastewater treatment using septic tanks as pretreatment is common. One challenge of decentralized wastewater treatment systems (DEWATS) is handling and utilization of the generated sludge. Sludge drying reed beds (SDRBs) are a robust method for dewatering and stabilization of sludge. Constructed wetlands (CWs) and SDRBs can be integrated to treat both wastewater and sludge. SDRBs require more area than most other sludge treatment options, but have low operational cost and energy requirements. The land area required for SDRB's can be optimized by the selection of an appropriate loading rate, sludge application frequency and resting phase. This paper gives a review regarding the use of SDRB's as well as presenting a pilot scale experiment comparing planted and unplanted sludge drying beds in Kathmandu. The planted beds showed a higher dewatering capability and higher reduction of volatile solids (VS). A short-term pilot-scale experiment can give valuable input to the design and operation of full-scale systems and for sub-tropical climate as that of Kathmandu Nepal, an initial sludge loading rate (SLR) of 100 kg total solids (TS)/m^2/year is suggested with a gradual increase to up to 250 kg TS/m^2/year.

Keywords

Sludge, Reeds, Dewatering, Evapotranspiration

1. Introduction

The management of sludge generated in decentralized wastewater treatment systems is a huge challenge in developing countries. In the Kathmandu valley there are about 68,000 septic tanks generating 75,000 m^3 of septic sludge (SS) annually [1]. Due to lack of sludge treatment facilities most of the sludge is disposed of untreated. A small fraction is used in agriculture, but the rest is illegally dumped into rivers, drains or open spaces. Sludge

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dewatering reed beds (SDRBs) present an exciting sludge treatment option for communities looking for alternatives to conventional sludge dewatering systems and can be used as a sludge treatment method at small as well as at large centralized treatment plants [2] [3]. When properly sized and constructed, SRDBs are effective for increasing the dry matter content of the sludge, thus reducing total sludge volume, while at the same time producing a safe, high quality end-product, which is often suitable for application to green areas or arable land [4] [5]. A properly constructed sludge dewatering reed bed system requires little maintenance, uses little to no electricity and can be loaded for 8 - 10 years before the sludge must be removed [6]. Although the evidence is limited planted sludge drying beds seem superior to unplanted and quicker dewatering, enhanced mineralization of residual solids, possibility of operating the beds at higher loading rates and longer life span of the bed is pointed out by several authors [7]-[9]. However, there are few studies that compare planted and unplanted beds under similar operating conditions [3] [10]-[12]. The challenges of using SRDB's are: long startup time due to conditioning of the reeds, sensitivity to the loading regime, wilting of plants and lack of design criteria for different sludge types and climate zones [2] [13]. The SLR is the main design parameter for sizing of the SDRBs, but the hydraulic loading rate (HLR) can also be used [6]. In the literature SLR vary from 17 - 28 kg $TS/m^2/yr$ for cold climate up to 250 $TS/m^2/yr$ in warm climate [13] [14]. For cold temperate climate and sludge from activated sludge plants with co-precipitation using iron or aluminum coagulants a SLR rate of 50 - 60 kg $TS/m^2/yr$ and a corresponding per capita area requirement of 0.3 - 0.6 m^2 has been used with good results [6]. In Norway and central Sweden, because of the cold climate, short growing season and freezing during winter a minimum area of 0.6 m^2/person equivalent and conservative SLR of 17 - 28 kg $TS/m^2/yr$, has been suggested [14]. In cold climates natural freezing and thawing processes aid the dewatering process [15] [16], but the systems have to be designed to accommodate the accumulating frozen sludge during the winter [14]. Freezing separates the solid and liquid fraction by the process of ice crystal formation. During the summer the ice crystals melt away leaving the consolidated and dewatered sludge [17]. Short dosing times and long resting periods have shown best results in cold climate [2] [18]. A preliminary recommendation for the design and mode of operation for tropical climate has been suggested by Koottatep [19]. A SLR of 250 kg $TS/m^2/yr$ and a loading frequency of once a week produced residual solids with TS content of 30% to 60% [20]. The equivalent per capita land requirement was 0.03 m^2/p.e., an order of magnitude lower than in colder climate. In Ghana a SLR of 100 - 200 kg $TS/m^2/year$ has been used to treat fecal sludge in unplanted sludge drying beds. These beds were able to remove the Helminths egg by 100% and the organic matter and solids concentration reduction was more than 80% [21]. In Yemen average dry solid content of 25% was achieved at a SLR of 178 - 283 kg $TS/m^2/year$ and drying time of 7 - 12 days [22]. Well documented design criteria exists for unplanted sludge drying beds [23] [24]. SRDBs follow this design regarding the construction of the bed with the exception that sometimes a more fine-grained layer, suited to nurse plants, is added at the top [25]. General design and operational criteria for SDRBs are given for cool temperate climate and tropical climate from the study of Nielsen [8] and Koottatep [19] respectively. Design and operating guidelines are not established for sub-tropical climate as that of Kathmandu. Dewatering efficiency of the beds depends on the sludge type, sludge quality and local climatic condition [26]. A short-term de-watering study can be helpful to provide rational information regarding parameters such as loading frequency, resting period and life expectancy of the bed [27]. The aim of the short-term study presented herein is to examine the dewatering performance of planted and unplanted drying beds treating septic tank sludge. Together with a literature review this study serves as input for suggesting design and operational parameters for SRDBs for sub-tropical climate as that of Kathmandu Nepal.

2. Materials and Method

2.1. Pilot scale Sludge Drying Beds

The pilot scale sludge drying beds are shown in **Figure 1**. The units consist of three identical beds with surface area 1.5 m × 0.7 m and a depth of 1m. Two beds were planted with *Phragmites Karkaa* (local reed) and one was left unplanted. The sequence and size of the filter media and the drainage layer were adopted from Koottatep [19] and is shown in **Figure 1**. A 50 cm freeboard above the surface layer was provided for sludge accumulation. The bottom of the bed was sealed using a plastic membrane. The drainage pipe was connected to a vertical pipe at one end to assist aeration from below. The water percolating from the bed was collected and measured. Scales were placed on the beds to measure the sludge accumulation in the beds. The change in sludge depth was recorded at short time intervals for first 24 hours and then at the end of the each resting period of one week.

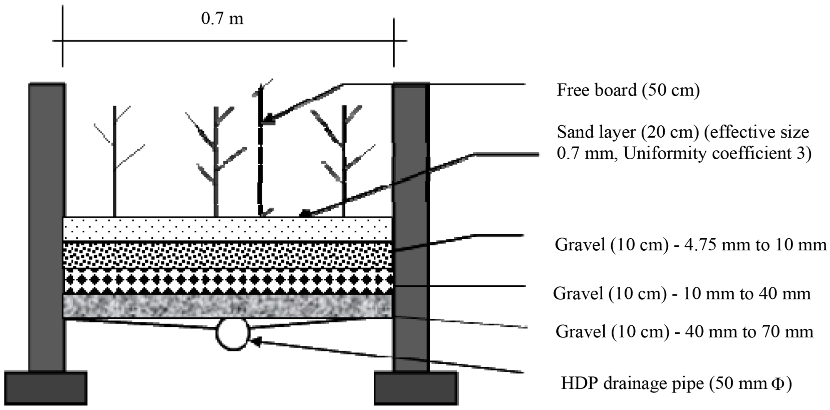

Figure 1. Cross sectional view of pilot scale sludge drying reed bed.

The beds had a plastic superstructure that allowed aeration, but prevented direct rainfall onto the beds. Prior to the actual experiment, the planted beds were conditioned by planting reeds (4 plants/m^2) and loaded with wastewater for a period of two months. The reeds were then well established and had reached a height of 90 cm prior to the sludge application.

The beds were loaded with a SLR of 250 kg TS/m^2/yr (Planted 1) and 100 kg TS/m^2/yr (Planted 2). The sludge was obtained from a private company cleaning septic tanks in Kathmandu. The sample from raw sludge was analysed before each loading cycle. The TS concentration of the septic tank sludge used for dewatering was different in each loading cycle. Therefore, to maintain the constant SLR for each loading cycle the depth of application varied. The average depth of application for SLR of 100 kg/TS/m^2 was 4.2 cm and for 250 kg TS /m^2/yr 12 cm. The sludge was fed every 7th day with 6 days resting between applications as suggested by Koottatep [28]. The duration of sludge loading and monitoring was 2 months and was conducted from December through January. The average daily high and daily low temperature during the experimental period was 8˚C and 20˚C respectively. Composite samples of the stabilizing sludge were collected at the end of each loading cycle by mixing equal portions of sample from 4 quadrants of the beds. The sludge was analysed for moisture content (MC), total solids (TS), VS, total Kjeldahl nitrogen (TKN) and total phosphorus (TP) using standard method of analysis [29].

Descriptive statistics (means, standard deviation) of the variables were examined. One-way Analysis of Variance (ANOVA) test at 95% confidence was used to compare the performance of the planted and unplanted beds and at different SLR.

2.2. Model for Estimation of Drying Period

The mass balances of all incoming and outgoing moisture can be used to compute the drying time [24] (**Figure 2** and Equation (1)). The drying time is a key operational parameter, because it gives the time between the loading cycles of the beds. The drying time required to achieve the desired dry solid content can be computed using Equation (1)

$$t = (1 - f_i) q_i + (1 - f_r) q_r - q_d / (f_e E_w) \quad (1)$$

where, t = required drying time, days; q_i = initial water content of sludge, kg/m^2; q_r = moisture received by precipitation, kg/m^2; q_d = moisture remaining in the dried sludge, kg/m^2, f_i and f_r are fraction q_i and q_r that is drained by gravity; f_e = reduction factor to account for reduced evaporation rate from a sludge surface; E_w = pan evaporation rate from a free water surface in kg/m^2/day. The monthly average of rainfall, temperature and class A pan evaporation in Kathmandu valley was obtained from Nayava [30].

3. Result and Discussion

3.1. Sludge Characteristics

Sludge may vary in composition depending on treatment system. When designing SRDBs it can be assumed

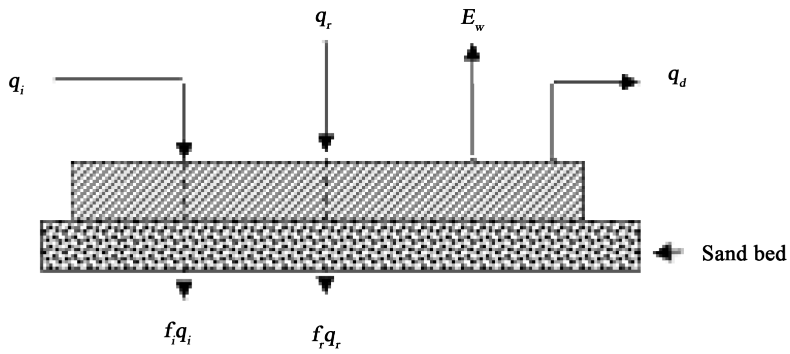

Figure 2. Conceptual illustration for computation of drying time in sludge drying reed bed [24].

that the characteristics of the sludge is important. In **Table 1** the septic tank sludge used in this study, is compared to other studies. Compared to sludge from activated sludge treatment plants the septic tank sludge is highly variable and in general has a higher TS content. The quality of septic sludge is affected by several factors as emptying intervals, emptying technology and design of the septic tank [31]. High concentration of solids indicates that the sludge has had a long storage time before being pumped out [32]. The emptying interval of septic tanks in Kathmandu is 3 to 3.5 years [1]. In a decentralized sludge treatment facility where the incoming sludge is expected to vary considerably, homogeneous mixing of sludge in a buffer tank is recommended, as this will equalize the TS concentration of the sludge [28].

Although it could be expected that the sludge from septic tanks also have a higher content of VS due to the long retention time, the content of VS is generally a bit lower, but not significantly different from the activated sludge systems. However, since the activated sludge is younger, the readily degradable part of the VS can be expected to be higher in the activated sludge, thus for the same amount of TS load the mineralization rate of organic matter can be expected to be higher for the plants receiving activated sludge. This implies that for the same climatic conditions higher organic and HLR should be possible for activated sludge than for septic tank sludge.

The TKN is higher in the septic sludge than for the activated sludge (**Table 1**). This difference is not easy to explain, but may be because up to 90% of the nitrogen in raw wastewater is in the ammonia state [34] and thus escapes with the liquid phase. Septic tank sludge has a higher TS content and more nitrogen is potentially held back as organically bound nitrogen. The phosphorus concentration is much higher in the activated sludge. The latter can be explained by chemical co-precipitation of phosphorus using aluminum or iron coagulants in the activated sludge plants (**Table 1**). Based on the parameters, TS, VS and TKN, and the limited number of investigations currently available it is difficult to generate a model predicting loading rates versus climate based on sludge quality, thus design of systems and selection of loading regime has to be based on empirical data.

3.2. Dewatering Rate and Drying Period

In order to operate SRDBs, the best possible dosing and drying cycles has to be determined as this can greatly influence the long-term capacity of the beds [2] [6] [13]. The fraction of the initial water content of the sludge that has percolated and evapotranspired in our pilot study is shown in **Table 2**. In all the beds, the percolation started between 10 to 20 minutes after the sludge loading and about 50% of the water content in the applied sludge drained from the filter within the first five hours. More than 97% of the percolation fraction emerged within the two first days. There was no significant difference (P = 0.017) in the fraction of water drained by gravity (f_i) between the planted and unplanted beds (**Table 2**).

The liquid mass balance of the experiment showed that 25% - 33% of the water content of the sludge is lost through evaporation or evapotranspiration and 58% - 63% was lost by gravity drainage. This is similar to results reported from a one-year long mass balance study of SDRBs in which around 35% of the water was accounted for by evapotranspiration and about 65% for gravity drainage [28]. Another short-term study [27] found that 60% to 70% of the water content in the sludge is typically free water that drains out by gravity. Comparing the planted and unplanted beds at SLR of 100 kg TS/m^2/yr the overall dewatering efficiency of the planted bed is

Table 1. Characteristics of raw sludge (Range/Average).

Parameter	Septic tank sludge (This study)	Septic tank sludge Kathmandu valley[1]	Septic tank sludge Bangkok[2]	Activated sludge with co-precipitation[3]
TS, mg/l	24,365 - 48,200 Avg. 30,160 (3.01%)	27,000 (mean of 42 samples) (2.7%)	2200 - 67,200 Avg. 19,000 (1.9%)	5000 - 13,000
VS (% of TS)	49 - 65 Avg. 58	65 (mean of 28 samples)	40 - 78 Avg.71	60 - 70
TKN mg/l (avg.)	1273 (1021 - 1500)	-	1000 (300 - 5000)	160
TP, mg/l	Avg. 23.4	-	-	71
SLR kg TS/m^2/year	100 and 250	250	140 - 360	50 - 70

[1][1], [2][28], [3][33].

Table 2. Fraction of water lost by percolation and evaporation/evapotranspiration and remaining TS content in the dewatered sludge (Average of 8 weekly samples).

	Fraction drained by gravity	Evaporated/Evapotranspired fraction
Planted (100 kg/m^2/year)	0.60 (±0.05)	0.33 (±0.05)
Planted 250 kg/m^2/year	0.58 (±0.01)	0.29 (±0.02)
Unplanted 100 kg/m^2/year	0.63 (±0.02)	0.25 (±0.02)

higher than the unplanted bed (see also **Table 3**) due to higher evaporation fraction in the planted bed. As the beds still were young during this study a larger effect of evapotranspiration can be expected when the roots are fully developed [32]. In SDRBs with matured plants, evapotranspiration of up to 64% is reported in a *Phragmites* stand [15]. In cold climate, where it takes a couple of years for the plants to mature, the SLR is gradually increased over the first years [8].

Drying time to achieve a final TS content of 40% for the planted beds have been estimated using the "f_i" value in **Table 2** and monthly climatic data for Kathmandu. Wetland evapotranspiration (ET) is approximated as about 0.7 - 0.85 times the class A pan evaporation [15]. Initial TS content of the raw septic tank sludge is assumed to be 4% (**Table 3**). The typical values of the coefficients f_r = 0.43 and f_e = 0.78 for anaerobically digested sludge have been adopted from [24]. The drying time estimated for each month is presented in **Figure 3**.

In this experiment the beds were covered, but the model (Equation (1)) allows prediction of the response in beds that are uncovered (open) and receives precipitation. For open beds, the estimated drying period required to achieve 30% TS content for SDRB varies from 13 days to 37 days for SLR of 250 kg TS/m^2/year and 6 days to 9 days for SLR of 100 kg TS/m^2/year. Longer drying time is required from June to September when precipitation is high and exceeds the evaporation. If the beds are covered the drying time in the months from June to September is significantly shortened. The rest of the year has more evaporation than precipitation and therefore the required drying times become shorter. In SDRBs with matured plants the movement of the plants helps to make cracks on the surface of the residual sludge layer providing channels for the rainfall to pass through the beds [27]. This will also help oxygen diffusion into the residual sludge promoting aerobic mineralization of the sludge [6]. Longer drying period will increase the TS concentration of the sludge, reduce the accumulated residual sludge volume, increase the life expectancy of the bed and, hence, reduce the restoration cost of bed [27]. However, in warm climates longer resting time could lead to plants suffering from aridity and consequently wilting [28]. When the drying periods are longer additional beds will be required to treat same amount of sludge, this will consequently increase the required bed surface area. Therefore, appropriate selection of the drying period is important for optimal performance as well as size of the system. A final total solid content of 40% - 50% can be theoretically achieved in sludge drying reed beds [35]. Correct loading and resting strategies based on local climatic conditions will maximize the dryness of the final residual sludge [6] [8] [14] [32]. In cold climate where evaporation and evapotranspiration is low it is recommended that beds are rapidly loaded within a few days and then allowed to rest for 30 to 50 days [8] [12] [26] [36].

3.3. Drying Bed Performance for TS, TP and TKN Removal

The TS, VS, TKN and TP contents of the dewatered sludge from the experimental beds after eight feeding and

Table 3. Average TS, VS, TKN and TP content measured at the end of each drying cycle (total 8 cycles).

Parameter	Raw Sludge*	Sampled after one week of resting period		
		Planted 1* (250 kg TS/m^2/year)	Planted 2* (100 kg TS/m^2/year)	Unplanted* (100 kg TS/m^2/year)
TS (%)	4 (±0.48)	20.94 (±2.6)	35 (±6.32)	24 (±2.00)
VS (% of TS)	64 (±5.37)	34 (±1)	27 (±5.57)	43 (±1)
TKN (% of TS)	3.2 (±0.971)	2.83 (±0.304)	2.24 (±0.60)	2.82 (±1.315)
TP (% TS)	0.05 (±0.00)	0.06 (±0.01)	0.05 (±0.01)	0.05 (±0.005)
Initial volume (lit)		122	52	52
Final volume (lit)**	-	10	3	6
Volume reduction (%)		92	96	89

*Mean based on analysis of 8 set of composite samples. **Final volume calculated using expression $V_1/V_2 = P_2/P_1$ [23]; where V_1 and V_2 are the initial and final volume of the sludge and P_1 and P_2 are the initial and final solid concentration of the sludge.

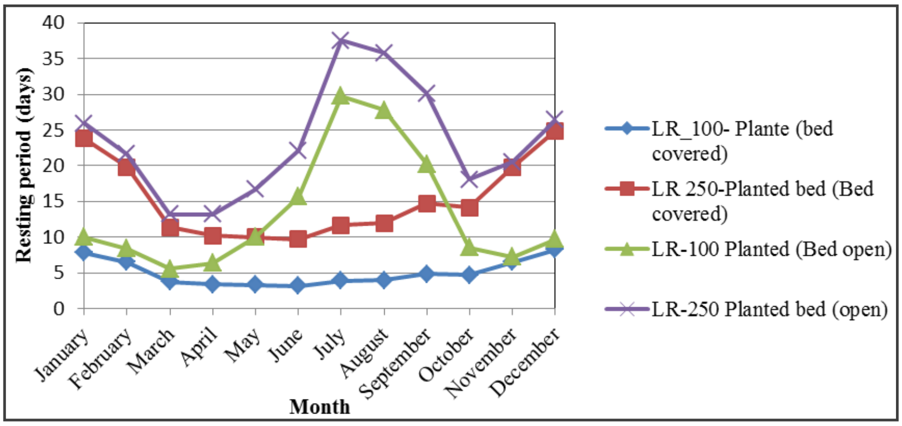

Figure 3. Estimated drying time for sludge treatment beds in Kathmandu for two different loading rates and covered/uncovered (open to precipitation) beds.

resting cycles are presented in **Table 3**. Comparison of planted and unplanted beds at SLR of 100 kg TS/m^2/y shows that planted beds produce sludge with a higher TS concentration than the unplanted beds. The planted bed loaded at 250 kg TS/m^2/y only had slightly lower TS than the unplanted bed loaded at 100 kg TS/m^2/y. Both planted beds show a higher VS reduction something that indicates better conditions for degradation of organic matter and thus higher mineralization rate in the planted beds.

There was slight reduction in TKN in the sludge after 2 months of operation. There was no significant difference in nitrogen mineralization in the planted and unplanted beds, but the planted bed loaded at 100 kg TS/m^2/year had the lowest TKN content and the planted bed loaded at 250 kg TS/m^2/year only had a slightly higher content than the unplanted bed. This indicates that nitrogen mineralization is more efficient in the planted beds. The reduction in TKN-content in the sludge is due to ammonia volatilization, plant uptake and nitrification reactions [2]. The planted beds also show a higher volume reduction, which indicates a both a higher mineralization rate and better dewatering capabilities.

The sludge depth is rapidly reduced within first 24 hrs. of sludge application due to rapid initial free drainage. After eight weeks of applications the depths recorded in Planted Bed 1 (250 kg TS/m^2/yr), Planted Bed 2 (100 kg TS/m^2/yr) and unplanted bed 3 (100 kg TS/m^2/yr) was 0.9 cm, 0.3 cm and 0.4 cm respectively. If sludge thickness (h_t) and resting time between each loading is known the life expectancy (T) of the bed can be calculated by using following expression [27].

$$T = (H/h_t) * t \tag{2}$$

where, H is freeboard for long-term sludge storage. Assuming a freeboard of 50 cm the life expectancy calculated are: 13 months for Planted Bed 1 (SLR 250 kg TS/m^2/yr), 38 months for Planted Bed 2 (SLR 100 kg TS/m^2/yr) and 29 months for Unplanted Bed (SLR 100 kg TS/m^2/yr). The simple model (2) does not account for mineralization and, thus underestimates the life expectancy. The drying efficiency of the bed affects the life expectancy of the system. In Denmark the operational cycle of the SDRB's in an average is 10 years with a final dry solid content of about 30% [2].

3.4. Comparison with Previous Studies and General Design Considerations

In **Table 4**, this study is compared with other case studies of SDRB's with respect to loading regime (loading rate and dosing/resting cycles) and final TS content. It is apparent from the table that the loading rates used in warmer climate are higher than in colder. Especially when considering that the data from the warmer climate is for systems receiving septic tank sludge that has a higher TS content than activated sludge. However, the empirical database is limited (**Table 4**) and does not provide data by which the loading regime can be modeled based on climate and sludge type. Due to lower evapotranspiration in cold climate rapid loading and prolong resting have been suggested [8]. In warmer climates a shorter resting period of a week or less seems to significantly increase the TS content in the sludge. In places of high precipitation partially covering of the bed would shorten the drying period. A prolonged resting period can be counterproductive in warm climate because of the possibility of wilting of plants. In both cold and warm climates a final sludge residue of at least 25% to 40% (**Table 4**) is achievable through proper operation of the bed. The experience in cold climate has shown that for the same TS load the rate of accumulation of activated sludge is higher than for septic sludge [37]. Therefore the desludging frequency of SDRB's treating activated will be higher.

The majority of the water content in the sludge is lost during normal operation period (loading and resting sessions) and the final resting phase does not significantly increase the dry matter content in the residual sludge [37]. However, the final resting period improves stability and the hygienic quality of sludge that is necessary for safe application in agricultural land. In Denmark 6 - 9 months of rest after the final application produce biosolids that meet the hygienic quality set by Danish guidelines [2]. The WHO guidelines [38] suggests more than 1 year resting in climate as in Kathmandu for fecal sludge. Due to limited data further experiment should be conducted in order to determine the optimal resting period for sub tropical climate.

With regard to composition of the filter design all the systems (**Table 4**) have top layer of sand from 15 cm to 25 cm thick over a gravel layer of 20 - 35 cm. The effective size of sand range from 0.3 mm to 1 mm and the gravel size range from 1cm to 4 cm. The systems in Denmark [26] use an additional 15 cm layer of silty loam above the sand. This layer promotes the initial growth of the reeds due to a large water holding capacity, but may induce more rapid clogging.

3.5. Conclusions

Sludge drying reed beds (SRDBs) are a technically simple method providing dewatering and sludge treatment

Table 4. Comparison of design and operation of sludge drying reed beds in different climatic zones.

Climatic Zone	Sludge type	SLR kg /m^2/year	Feeding and resting strategy	TS content of dewatered sludge (%)	Reference
Temperate	AS	50 - 60	3 days loading and 30 to 50 days rest period	≥30	[26]
	SS	25 - 30	20 days rest period in between loading	70%	[39]
	SS	46	1 week loading and 5 weeks rest period	38%	[12]
Continental	AS	85 - 90	1 week loading and 3 weeks resting in winter and 1 to 2 weeks resting in summer	50% - 64%	[35]
	AS	50 - 60	2 days loading and 10 days rest period	26% - 30%	[40]
Tropical	SS	178 - 283	7 - 12 days resting period between each dosing	40%	[20]
	SS	100 - 200	7 days of resting between each loading	≥30%	[4]
Humid sub-tropical climate	SS	100	7 days of resting between each loading	35 (±6.32)	This study

capabilities comparable or exceeding most other sludge handling methods. The method can handle any type of sludge, but if the sludge quality varies, mixing of the sludge prior to application in SRDBs is recommended. This experiment showed that:

- The overall dewatering efficiency of the planted bed was higher than the unplanted bed due to higher evaporation fraction in the planted bed. As the beds still were young during this study a larger effect of evapotranspiration can be expected when the roots are fully developed.
- The planted beds had a higher VS reduction than unplanted beds indicating better conditions for degradation of organic matter and thus higher mineralization rate in the planted beds.
- A short-term pilot-scale experiment can give valuable input to the design and operation of full-scale systems.

Based on the limited number of investigations currently available it is difficult to generate a model predicting loading rates versus climate based on sludge quality parameters, thus design of systems and selection of loading regime has to be based on empirical data.

Based upon this short-term experiment and literature data, an initial sludge loading (SLR) rate of 100 kg TS/m^2/year is suggested for the sub-tropical climate as that of Kathmandu. However, after one year of operation, when the plants are matured, the SLR can be gradually increased up to 250 kg TS/m^2/year. A minimum resting period of one week between loadings and final resting phase of one year can ensure both adequate dewatering as well as a hygienized and stable end products. This study as well as other studies has shown that in warm climates with high annual precipitation partially covered beds will reduce the drying time and consequently require less area than open beds.

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