DEWATERING AND STABILIZATION OF SLUDGE RESIDUE IN SLUDGE TREATMENT REED BEDS TREATING SEPTAGE

Yu Zhe Huong[1], Yee Yong Tan[1,*], Fu Ee Tang[1], Agus Saptoro[2,3]

[1]Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, Miri, Sarawak 98009, Malaysia

[2]Department of Chemical and Energy Engineering, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, Miri, Sarawak 98009, Malaysia

[3]Curtin Malaysia Research Institute (CMRI), Curtin University Malaysia, CDT 250, Miri, Sarawak 98009, Malaysia

*Corresponding Author: tan.yee.yong@curtin.edu.my

***ABSTRACT*:** *The accumulation of sludge residue in the sludge treatment reed bed (STRB) significantly reduces the bed permeability, which further affects the efficiency of sludge dewatering and stabilization. The solids loading rate (SLR) and resting period are the most crucial operating parameters in STRBs that govern the sludge residue accumulation. This study investigated the accumulation rate of sludge residue in laboratory-scale STRBs treating septage under varying SLRs and resting periods, as well as its roles in sludge dewatering and stabilization. This study showed that high SLR increased the thickness and moisture content of sludge residue, while the variation in the resting period had a minimal effect on the sludge accumulation and associated dewatering efficiency. Drainage flow from the STRBs tended to increase with SLR, but a high SLR reduced bed permeability due to the rapid accumulation of sludge residue on the bed surface that hindered the drainage dewatering. Further, the extended resting period helped to maintain the drainage dewatering. In addition, a low SLR improved the sludge stabilization efficiency, while an extended resting period favoured the degradation of volatile organic matter.*

Keywords: Sludge Treatment Reed Bed; sludge dewatering; sludge residue layer; solids loading rate; resting period

1. INTRODUCTION

In Malaysia, improper management of septage, which is the sludge removed from septic tanks, leads to environmental issues such as water and land contamination. The Sludge Treatment Reed Bed (STRB) system has attracted increasing attention as a sustainable septage management system due to its excellent dewatering and stabilization efficiency, low energy consumption, and simple and chemical-free operation [1]. A STRB is a vegetated granular bed where the raw septage is loaded onto the top bed surface in batch. The bed physically traps the solids, and the liquid is freely drained from the bottom of the bed, which is known as drainage dewatering. Such a dewatering mechanism generally reduces 60% of the sludge volume [2]. The retention of the solids at the top bed surface forms a layer of sludge residue layer. The water content of this layer is high when it is just formed, and evapotranspiration occurs during the resting period that further dewaters the sludge deposit to meet the disposal standard, which is the so-called evapotranspiration dewatering [3]. At the same time, the volatile organic matter is degraded through microbial-induced mineralization processes, stabilizing the sludge to ensure safe disposal [1].

The operation of STRB is always hindered by the problem of waterlogging, resulting in prolonged surface ponding and low drainage dewatering [4]. The waterlogging problem is usually attributed to bed clogging caused by the excessive accumulation of sludge residue, which reduces the permeability of the reed bed and hinders water infiltration [2]. The prolonged surface ponding requires a longer resting period to dewater the sludge deposit through gravity drainage evapotranspiration. Moreover, the high moisture content deteriorates the mineralization rate of the volatile organic matter in the sludge deposit [4]. The operating parameters, including the loading rate and resting period, are regarded as the most crucial factor of sludge residue accumulation and the efficiency of dewatering and stabilization [1, 2]. The solids loading rate (SLR) of STRBs in tropical regions is generally around 100 kg/m^2/year with an annual sludge accumulation of 6 cm, while the resting period ranges from days to months in the literature [6].

Although the literature provided valuable insights into the design of the loading rate and resting period in STRB, there is a need to study the influence of sludge residue accumulation on the overall sludge dewatering and stabilization. This study aims to investigate the accumulation rate of sludge residue in laboratory-scale STRBs under varying loading rates and resting periods. The relationships between the sludge residue accumulation and the sludge dewatering and stabilization performance were also identified.

2. MATERIALS AND METHODS

A total of five STRBs were constructed at Curtin University Malaysia, Miri, Malaysia. Each bed was accommodated in a 55-gallon water barrel, which has a diameter of 0.5 m or a surface area of 0.196 m^2. The granular bed has a height of 0.4 m, which consists of (from bottom to top) 0.15 m coarse aggregates (diameter 50 – 60 mm), 0.10 m medium-sized aggregates (diameter 25 - 37.5 mm), and 0.15 m small-sized aggregates (diameter 4.75 - 9.75 mm). A 0.4 m freeboard was provided for each bed. Each bed was planted with fourteen common reeds (*Phragmites karka*). All beds were acclimatized with diluted sludge to build up a sludge residue layer with a depth of approximately 40 to 50 mm and stimulate the growth of reeds and microorganisms. The system was located under the roof to exclude the impact of rainwater.

The raw septage was collected from the household areas and stored in a 400-gallon tank. Then, the raw septage was homogenized through manual mixing and transferred into a 50-gallon container to ensure the consistency of quality in each loading cycle. Before loading, the solids (TS) concentration of the raw septage was measured based on the Standard Methods for the Examination of Water and Wastewater 2540G. Then, the volume of raw septage to be fed in each bed was determined according to the TS concentration, SLR, and resting period. The loading rate, resting period, and the number of loading cycles are summarized in Table 1. In summary, Bed 1, 2, and 3 were used to assess the influence of SLRs, while Bed 2, 4, and 5 were used to investigate the effect of resting periods.

Table 1. Loading Regime of STRBs

Bed	Solids Loading Rate (kg/m^2/yr.)	Resting Period (day)	Number of Loading Cycles
1	50	6	6
2	100	6	6
3	150	6	6
4	100	3	12
5	100	9	4

After the loading, the volume of the drainage water was measured to assess the efficiency of drainage dewatering. Then, the increment of thickness in the sludge residue was measured using a ruler on a daily basis until the following loading. In addition, three samples of sludge residue were collected from each bed daily to evaluate the efficiency of sludge dewatering and mineralization during the resting period based on the changes in moisture content and total volatile solids (TVS). ASTM D2216 was adopted to measure the moisture content in the sludge residue, while the fraction of TVS in the residue was determined using Standard Methods for the Examination of Water and Wastewater 2540E.

3. Results and Discussions

3.1. Total Solids Concentration and Loading Volumes

Table 2 summarizes the TS concentration and the corresponding loading volume in each STRB throughout the experiment. The TS concentration of the raw septage varied widely, resulting in varying loading volumes from batch to batch. The maximum and minimum TS concentrations were 55.78 g/L and 18.78 g/L, respectively. In general, the high TS concentrations resulted in a low loading volume. In addition, the loading volumes of Bed 1, 2, and 3 reflect that the higher the SLR, the higher the total loading capacity at the same resting period. Meanwhile, Bed 2, 4, and 5 show that the variation in resting rate only changed the loading volume in each cycle, while the total loading volumes were almost the same over the loading periods.

3.2. Thickness and Moisture Content of Sludge Residue

Figure 1 and Figure 2 show the variation in sludge residue thickness of beds with varying SLRs and resting periods, respectively. Besides, Table 3 summarizes the increment of sludge thickness over the experimental period. Generally, the sludge residue thickness increased significantly on the day after the loading, followed by a gradual decrease over the resting period. Decreased sludge residue thickness is attributed to continuous water loss via evapotranspiration during the resting period, resulting in the shrinkage of sludge [5].

Table 2: TS concentrations and loading volume

Loading Cycle	TS (g/L)	Loading Volume in STRBs (L)				
		Bed 1	Bed 2	Bed 3	Bed 4	Bed 5
1	19.16	8.54	17.08	25.62	8.54	25.62
2		-	-	-	8.54	-
3	18.78	8.71	17.42	26.14	8.71	-
4		-	-	-	8.71	26.14
5	29.97	5.46	10.91	16.38	5.46	-
6		-	-	-	5.46	-
7	55.78	2.93	5.87	8.80	2.93	8.80
8		-	-	-	2.93	-
9	20.37	8.03	16.07	24.11	8.03	-
10		-	-	-	8.03	24.11
11		8.03	16.07	24.11	8.03	-
12		-	-	-	8.03	-
Total		41.7	83.42	125.16	83.42	84.67

The higher SLR resulted in a more significant sludge residue accumulation, where the increments of sludge residue thicknesses in beds with 50, 100, and 150 kg/m^2/yr. were 2.17, 5.17, and 6.83 cm, respectively. The observation agreed with the findings in Reference [7], where the sludge accumulation could be estimated as a function of solids load. The relationship between the sludge residue thickness and the shrinkage was also observed from the moisture content variation, as shown in Figure 3. The moisture content was maximum after loading and gradually decreased during the resting period, with a trend consistent with the sludge residue thickness and explaining the shrinkage effect. The moisture contents in Bed 1 with the 50 kg/m^2/yr. were below 70% at the end of the resting period, and the moisture content could be as low as 40%. In contrast, the moisture contents in the other beds were between 70 and 80%. It is due to high SLR resulting in higher hydraulic loads, which caused the bed surface to remain waterlogged and take longer to dry out [1].

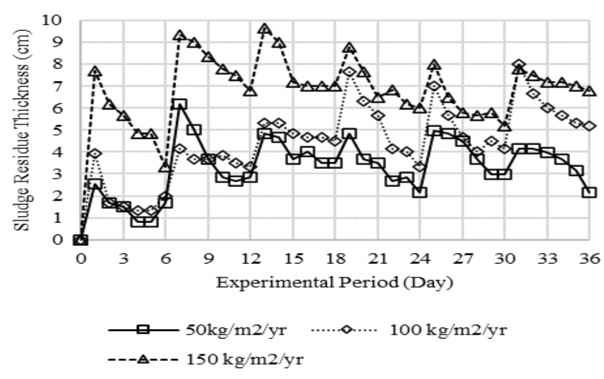

Figure 1. Variation in sludge residue thickness under varying SLRs

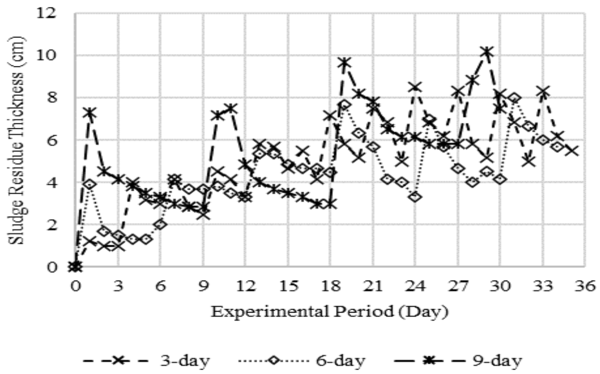

Figure 2. Variation in sludge residue thickness under varying resting periods

Table 3. Loading Regime of STRBs

Bed	Initial Thickness (cm)	Final Thickness (cm)	Increments (cm)
1	5.33	7.50	2.17
2	4.33	9.67	5.17
3	4.50	11.33	6.83
4	4.50	10.00	5.50
5	5.50	11.67	6.17

In contrast, no clear trend was found for the sludge residue accumulation under varying resting periods. Although a significant increase in sludge residue thickness was observed after loading in Bed 5 with a rest period of 9- days, the sludge residue shrunk more to a similar final thickness as the beds with a rest period of 3- and 6-day (Bed 4 and Bed 2, respectively), which ranged from 5 to 6 cm. Typically, an extended resting period reduces the volume of sludge residue in the reed beds [8]. The similar thickness of sludge residue found in this study was attributed to the high hydraulic load in the bed with a more extended rest period, thus resulting in similar levels of dewatering despite more extensive evapotranspiration. This observation was also validated by

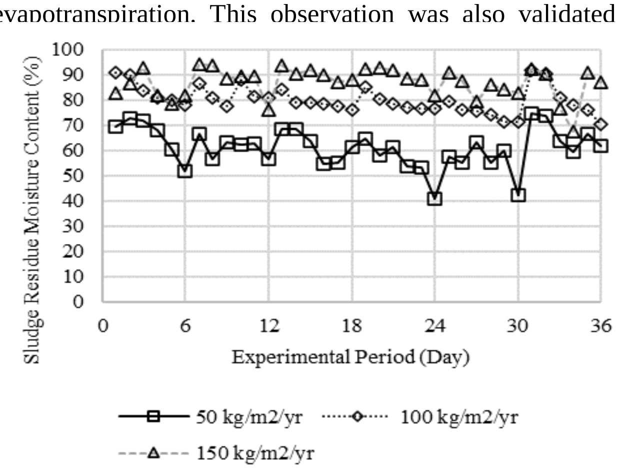

Figure 3. Variation in sludge residue moisture content under varying SLRs

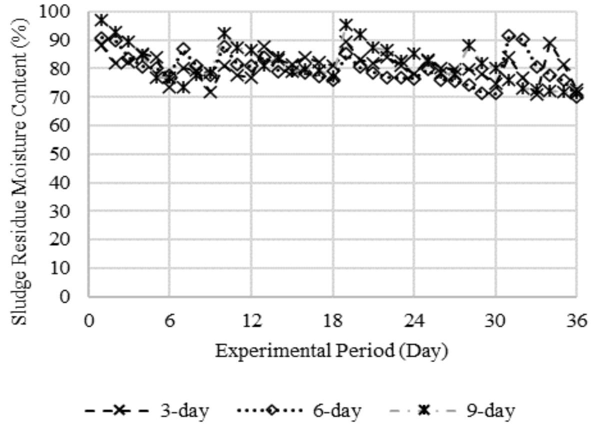

Figure 4: Variation in sludge residue moisture content under varying resting periods3.3. Drainage

Efficiency

Table 4 summarizes the average water recovery percentage via drainage in each bed throughout the experiment. Generally, the percentages were between 50 to 65%, which was similar to the existing studies [2, 8]. For the effect of SLR, Bed 2 with 100 kg/m^2/yr. was measured with the highest average water recovery percentage, 63.51%. The lowest water recovery in Bed 1 with 50 kg/m^2/yr. was due to the low hydraulic load throughout the experiment, resulting in a slow drainage flow. The dependence of the drainage efficiency on the hydraulic load was also observed in load cycle 7. The water recovery was only 16% as the hydraulic load was only 2.93 L. High hydraulic loads typically result in deeper surface ponding, creating a significant head difference and thus accelerating drainage flow rates, and, therefore, the variation in the drainage rate of STRBs always depend on the hydraulic load [7]. However, Bed 3, which was operated at 150 kg/m^2/yr. and with the highest hydraulic load, had a lower average water recovery percentage than Bed 2. The high solid load in Bed 3 resulted in a thick sludge residue layer, which characterized low permeability and resistance to water infiltration, leading to a lower water recovery [9].

Based on the results of beds 4, 2, and 5 operated with 3-, 6- and 9-day resting periods at the same SLR, respectively, there was an increasing trend in water recovery with more extended rest periods. Based on Table 2, the hydraulic loads in the beds with a longer resting period were higher in each loading cycle, resulting in a more rapid drainage flow, as explained earlier. Moreover, the highest water recovery obtained in Bed 5 can be explained by the continuous loss of moisture content through evapotranspiration that caused the formation of surface cracks in sludge residue during the resting period, which was beneficial to bed permeability [4]. Accordingly, an appropriate resting period shall be implemented to prevent the waterlogging problem in STRBs.

Table 4. Average Water Recovery Percentage in STRBs (%)

Bed 1	Bed 2	Bed 3	Bed 4	Bed 5
52.87% ±17.60%	63.51% ±15.97%	56.96% ±9.94%	55.46% ±8.35%	64.44% ±14.67%

3.4. Sludge Stabilization

During the resting period, sludge mineralization degrades the volatile substances to improve the quality of the final sludge residue before disposal. The ratio of TVS and TS, also known as the volatile solids fraction, was used to assess the sludge stabilization efficiency in the sludge residue. Figure 5 and Figure 6 show the variation in the TVS/TS ratio of sludge residue with varying SLRs and resting periods, respectively. Table 5 summarizes the average TVS/TS ratio of sludge residue throughout the resting periods. Overall, the sludge residue in all beds was high in volatile solids during the early stages, but the fraction decreased and maintained around 30 to 40% for the remainder of the experiment.

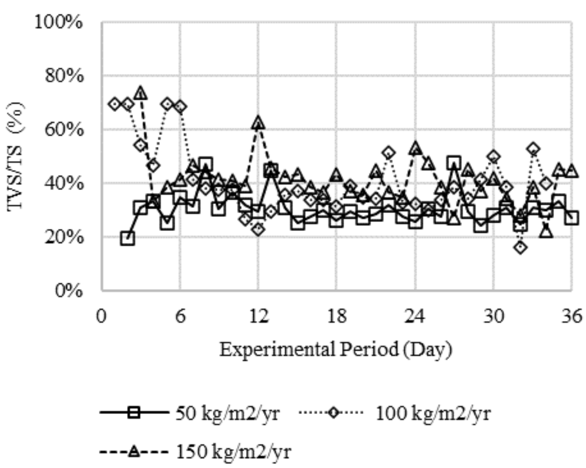

Figure 5. Variation in TVS/TS (%) of sludge residue under varying SLRs

Table 5 shows that Bed 1, operated at a 50 kg/m2/yr. SLR, had the lowest average TVS/TS ratio of 30.57%, with only three samples having ratios higher than 40%. Meanwhile, in Bed 2 and 3, which were operated with higher SLRs, the average TVS/TS ratios were around 40%. The better sludge stabilization efficiency in the bed with low SLR was due to the better dewatering in the sludge residue, as the low moisture content promotes aerobic mineralization to degrade the volatile matter [1].

However, the effect of resting periods was less significant, as the average TVS/TS ratios for Bed 4, 2, and 5 were between 38 and 40%. Nonetheless, the bed with the 9-day resting period, namely Bed 5, produced consistently low TVS/TS ratios throughout the experiment. The literature emphasized the importance of a sufficient resting period for stabilizing volatile organic matter in sludge residues, where waterlogged conditions due to the overloading of reed beds can lead to anaerobic conditions and limit the efficiency of sludge stabilization, and thus a longer resting period should be implemented [11]. It is also common to have a final resting period of up to months to minimize the amount of volatile organic matter before emptying sludge residue from the STRBs [8].

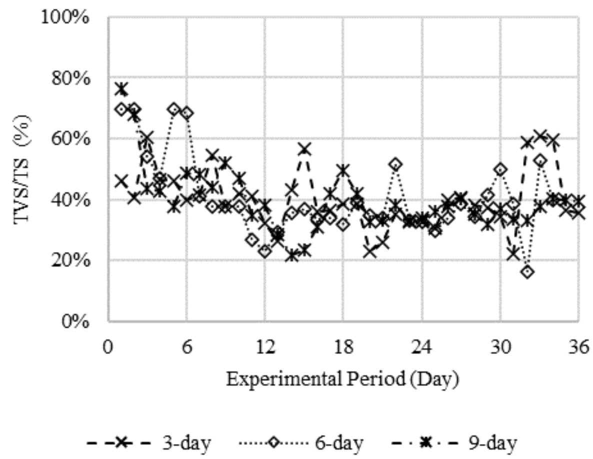

Figure 6. Variation in TVS/TS (%) of sludge residue under varying resting periods

Table 5. Average TS/TVS of sludge residue throughout the resting periods in STRBs (%)

1	2	3	4	5
30.57% ±5.86%	39.83% ±12.17%	41.36% ±9.16%	40.02% ±10.08%	38.73% ±8.40%

3.5. Overall Performance of STRBs

The moisture contents of the sludge residue layer in Bed 1 and 2 were below 80% after the resting period, which met the requirements of dry solid contents of at least 20% before disposal, as per the National Water Services Commission guidelines in Malaysia [12]. Therefore, under tropical climates, SLRs of 50 and 100 kg/m^2/yr. are adequate for septage treatment in the proposed STRB. However, the SLR of 150 kg/m^2/yr. was too high and exceeded dewatering capabilities, as a thick sludge residue layer was formed and hindered the drainage dewatering. The water recovery from drainage dewatering in Bed 1 was significantly lower than in Bed 2, subsequently reducing the effluent treatment capacity required as most moisture contents were released via evapotranspiration. In addition, the sludge stabilization was also more efficient in the bed with lower SLRs, where the TVS/TS ratio of sludge residue was lower throughout the experiment. However, the main disadvantage of low SLR is the large amount of surface area required. Although the sludge residue in the bed with a SLR of 100 kg/m^2/yr. characterized higher moisture and organic content and discharged more effluent, the surface area requirement was only half of the bed with a SLR of 50 kg/m^2/yr. Therefore, land availability is a crucial factor in determining the loading regime of STRBs.

On the other hand, the resting period plays a minor role in the sludge residue accumulation and sludge dewatering and stabilization. In this study, the resting periods of 3-, 6-, and 9-day produced adequate moisture and volatile solids contents in the sludge residue at a SLR of 100 kg/m^2/yr. A more extended resting period can reduce the operating frequency and minimize the operation expenditure, but a main concern is that a minimum moisture content should be maintained to support the growth of macrophytes [1].

4. CONCLUSION

This study gained important insights into the sludge residue accumulation and sludge dewatering and stabilization in STRBs treating septage at different loading rates and resting periods. The conclusions of this study are as follows:

- The moisture contents in the beds operated at SLRs of 50 and 100 $kg/m^2/yr$ were below 80% after the resting period, which met the requirements of dry solid contents of at least 20% before disposal.
- The average TVS/TS ratios of all beds were around 40%, implying adequate sludge stabilization efficient in the proposed STRBs.
- The bed operated at a SLR of 50 $kg/m^2/yr$ achieved the highest sludge dewatering and stabilization efficiency.
- The bed operated at a SLR of 150 $kg/m^2/yr$ was observed with a significant sludge residue buildup, which hindered the drainage dewatering and failed to meet the requirements of dry solid contents of at least 20% before disposal.
- The dependency of drainage dewatering on the hydraulic loads in STRBs were observed.
- The effect of the resting period were minimal in the sludge residue accumulation and sludge dewatering and stabilization, but a more extended resting period was able to maintain the bed permeability through the formation of surface cracks in the sludge residue layer.
- Although the SLR of 50 $kg/m^2/yr$ delivered the best performance, the SLR of 100 $kg/m^2/yr$ is still a feasible loading regime as it significantly reduces the land requirement.
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Acknowledgements

The authors would like to acknowledge the financial support given by the Fundamental Research Grant Scheme (FRGS/1/2020/TK0/CURTIN/03/3) from the Ministry of Higher Education (MOHE), Malaysia. The authors would also Huey in the experiments. like to thank the help of Chong Jia Xuen and Sabrina Ha Chian

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