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**Research Paper**

# Influence of sludge deposit layer on sludge treatment reed beds treating septage

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## ABSTRACT

There is a lack of study on the influence of the sludge deposit layer on the performance of sludge treatment reed beds (STRBs) treating septage as well as the sludge deposit characteristics due to the operational parameters of solids loading rate (SLR) and resting periods. The laboratory-scale STRB was operated under varying SLRs and resting periods to investigate the sludge deposit characteristics, dewatering efficiency, and the quality of the rejected water. Inadequate operation, such as excessive loading and insufficient resting period, resulted in prolonged surface ponding, and the total solids (TS) content failed to meet the disposal standard of 20%. This study found that the STRB operated with 100 kg/m$^2$/year SLR and 6-day resting period performed the best in sludge dewatering and stabilization, as the final TS content and total volatile solids/TS ratio of the sludge deposit were 23 and 33%, respectively. Meanwhile, the moisture content always remained higher than the plastic limit, preventing severe surface cracking that led to poor rejected water quality. In addition, the average COD and TS removals in the rejected water from all STRBs reached 96 and 88%, respectively, revealing that the proposed system is promising and reliable in treating septage.

**Key words:** resting period, sludge dewatering, sludge stabilization, solid deposits, solid loading rate

## HIGHLIGHTS

- The changes and overall increment of sludge deposit layer thickness under varying loading regime were discussed.
- The moisture content of the sludge deposit and its respective plastic limit was determined to prevent possible cracks on the sludge deposit layer.
- The accumulation of the sludge deposit is crucial to the sludge dewatering and stabilization efficiency, and its properties are highly dependent on the loading regime.

## 1. INTRODUCTION

Sludge treatment reed bed (STRB) has become an attractive system to dewater and stabilize septage, a mixture of excreta and blackwater removed from septic tanks (Tayler 2018). In general, STRB is capable of dewatering the septage to a final solid content above 20% with minimum energy (SPAN 2008; Nielsen & Stefanakis 2020). In addition to its low energy consumption and simple operation advantages, STRB does not involve any chemicals during the treatment, and the stabilized sludge deposits can be safely disposed of or used as fertilizers (Brix 2017). Furthermore, it has been reported that the concentrations of chemical oxygen demand (COD), total solids (TS), and total nitrogen in the rejected water from STRBs are reduced by more than 80% (Tan *et al.* 2017). However, the highly variable septage characteristics and inappropriate operation practices in STRBs, such as septage overloading or insufficient resting periods, could result in poor sludge dewatering and stabilization (Li & Yuan 2023). Therefore, further study is needed to investigate the optimal operating practice to ensure the safe disposal and reuse of stabilized septage.

In STRB, the retention of the particulate contaminant at the top surface of the granular bed forms a layer of low permeable deposit (Khomenko *et al.* 2019). The accumulation of sludge deposits compacts the sludge layer and reduces the effective

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porosity and permeability of the beds, subsequently resulting in ‘compressible cake filtration’ that improves the solid retention but deteriorates the sludge dewatering efficiency (Höfgen *et al.* 2019). Moreover, the organic content is also a factor in the hydraulic properties of the sludge deposit layer, in which a high fraction of volatile solids increases the specific resistance that hinders the separation of liquid and solid during the dewatering process (Trein *et al.* 2019). Therefore, the excessive layer of sludge deposit is meant to be removed regularly to prevent prolonged ponding in STRB and to ensure the desired dewatering performance.

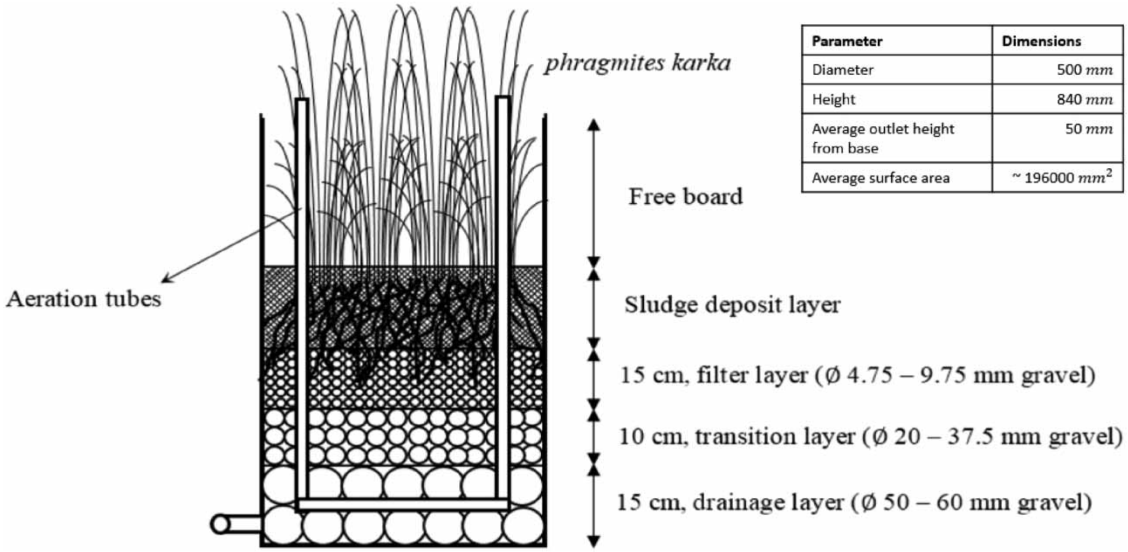
The solids loading rate (SLR) and resting period are regarded as the main design parameters in the TS fed onto per surface area of the bed in a year (Tan *et al.* 2023). The selection of SLR should ensure a sufficient sludge volume loaded into the bed to support the vegetation growth during the resting period while achieving adequate drying of the sludge deposit (Tan *et al.* 2017). SLR is also the main parameter in the accumulation of sludge deposits in the STRBs. Under the tropical climate, the SLR can be up to 100 kg/m$^2$/year due to high temperatures that enhance the evapotranspiration rate, thereby improving the dewatering efficiency (Gholipour *et al.* 2022). Meanwhile, the duration of the resting period determines the dewatering and stabilization performance in the sludge deposit layer. A typical resting period for an STRB is a week (7 days), which makes economic and operational sense (Osei *et al.* 2019; Wang *et al.* 2022). The large volume but less frequent sludge loading has the advantage of less workforce involvement, subsequently reducing the operational cost. However, past studies investigated the effluent treatment efficiency more and neglected the influence of sludge deposits drying over the STRB performance. Recently, the study of sludge deposits has gained attention in the field of microbial activities in sludge stabilization (Hu *et al.* 2020; Kowal *et al.* 2021).

This study aims to investigate the effect of sludge deposit accumulation on the overall dewatering and stabilization efficiency, which is lacking in the current studies. The knowledge gained from this research will contribute to the design and operation recommendations of STRBs, thus solving the problem of improper septage management with sustainable technology.

## 2. MATERIALS AND METHODS

### 2.1. Laboratory-scale STRB and loading regime

Six laboratory-scale STRBs were constructed at Curtin University Malaysia, Miri, Sarawak, in a 55-gallon polyethylene tank with a surface area of 0.2 m$^2$. The reed bed consists of several layers of porous medium, where the arrangement from top to bottom is a 0.15-m-thick filter layer (crushed stone with 4.75–9.75 mm diameter), a 0.10-m-thick transition layer (crushed stone with 20.00–37.50 mm diameter), and a 0.15-m-thick drainage layer (crushed stone with 50.00–60.00 mm diameter), as shown in Figure 1. Each reed bed was planted with eight clumps of common reeds (*Phragmites karka*) with at least 0.05 m distance between each other. Then, the reed beds were acclimatized with diluted septage for 2 months, and a 1-



| Parameter | Dimensions |
|---|---|
| Diameter | 500 $mm$ |
| Height | 840 $mm$ |
| Average outlet height from base | 50 $mm$ |
| Average surface area | ~ 196000 $mm^2$ |

**Figure 1** | Enlarged cross-sectional view of STRB.

month preliminary treatment was carried out before the actual experiment data collection. A layer of sludge deposit was formed after the acclimatization period. In addition, two vertical perforated pipes were installed to promote aerobic conditions in the deeper layer of the reed beds. All laboratory-scale STRBs were located within the transparent roof area to exclude the effects of precipitation while not compromising the evapotranspiration rate.

The experimental study was carried out continuously from July 2022 to December 2022. The raw septage was retrieved from domestic households and stored in a 400-gallon tank. The septage was homogenized by manual stirring before transferring from the storage tank to the reed beds. The STRBs were operated under varying SLRs and resting periods. The SLRs applied in this study were 50, 100, and 150 kg TS/$m^2$/year. After loading, the rejected water was allowed to drain freely. Then, the reed beds were rested for 6–27 days. Table S1 shows the loading conditions in each STRB.

### 2.2. Analysis of a sludge deposit layer

In this study, the variation in the thickness of the sludge deposit layer was measured daily over the loading–resting cycle. Three measurements were performed on a daily basis, and an average thickness value was then calculated. In the meantime, three samples of sludge deposits were collected from each bed to evaluate the sludge dewatering efficiency by measuring the moisture content (MC) based on the ASTM D2216 2019 oven-drying method. The total volatile solids (TVS) fraction in the sludge deposit was also determined using the United States Environmental Protection Agency (USEPA) method 11684 to assess the sludge stabilization performance. Moreover, the plastic limit (PL) of the sludge deposit was also obtained using the ASTM D4318-17 method. This parameter indicates the minimum water content that causes the permanent deformation of sludge deposits, and it is referred to as an indicator parameter for sludge cracking in STRBs over the resting period.

### 2.3. Volumetric and quality analysis of rejected water

The collection of rejected water was done continuously throughout the resting period to determine the drainage efficiency through gravity drainage. The discharge flux of rejected water (m/min) was estimated from the volume of collection within the specified time interval. Thus, the discharge flux is given as

$$\text{Effluent Flux (m/min)} = \frac{V_{\mathrm{ei}}}{A \times t_i} \tag{1}$$

where $V_{\mathrm{ei}}$ is the volume of effluent collected ($m^3$) within the time interval $t_i$ (min) and $A$ is the area of reed bed ($m^2$). The total water recovery can also be determined through the total volume of rejected water collected. The percentage of water recovery was the fractional amount of the effluent to the influent, hence

$$\text{Water Recovery (\%)} = \frac{\sum_{i=0}^{N} V_{\mathrm{ei}}}{V_0} \times 100\% \tag{2}$$

where $N$ is the number of samplings and $V_0$ is the hydraulic load ($m^3$).

The raw septage and rejected water samples were collected in plastic Biochemical Oxygen Demand (BOD) bottles to evaluate treatment performance in the STRB. The concentrations of nitrate ($NO_3^-$), pH, and dissolved oxygen (DO) were measured using a portable multiparameter meter (HACH HQ40d) with ion-selective probes. The COD was analyzed using a spectrophotometer (HACH DR2800) with digested vials. Meanwhile, the TS concentration was measured through the ASTM D2216 2019 oven-drying test. The treatment performance was determined according to the mass removal efficiency as follows:

$$\text{Mass Removal Efficiency (\%)} = \frac{C_0 V_0 - \sum_{i=0}^{N} (C_{\mathrm{ei}} V_{\mathrm{ei}})}{C_0 V_0} \times 100\% \tag{3}$$

where $C_0$ and $C_{\mathrm{ie}}$ are the concentrations of the influent and the effluent (mg/L), respectively.

## 3. RESULTS AND DISCUSSION

### 3.1. Initial concentration and loading volume

The TS concentration and corresponding loading volume required for each reed bed are shown in Table S2. The TS concentration ranged from 10,800 to 20,400 mg/L, and the average TS concentration was 16,700 ± 4,100 mg/L. Since each bed used a fixed SLR, the loading volume was larger when the TS concentration in the raw septage was lower. In addition, the beds with higher SLR or longer resting periods allowed for a larger septage load. The average concentrations of COD, DO, $NO_3^-$, and pH in the raw septage were 4,800 ± 1,900, 0.24 ± 0.12, 340 ± 110, and 7.9 ± 0.4 mg/L, respectively. According to the literature, the septage quality was classified as a low-strength fecal sludge due to the relatively low TS and COD concentrations (Zewde *et al.* 2021).

### 3.2. Sludge deposits

Table 1 shows the initial and final sludge deposit thickness in each bed over the experiments. The initial sludge deposit thickness of Bed 1 was the lowest at around 7 cm due to the low loading volume during the pretreatment stage as per the designed SLR, while the initial sludge deposit thicknesses in other beds were approximately 11 cm. The continuous loading of septage onto the reed beds gradually increased the existing sludge deposit layer thickness. In summary, the sludge deposit accumulation was proportional to the solids loads. In Bed 1, the thickness increased by roughly 0.2 cm with an SLR of 50 kg TS/$m^2$/year. In contrast, sludge accumulations were around 9 and 10 cm in beds with 100 and 150 kg TS/$m^2$/year, respectively. It was observed that the sludge accumulation rates increased with more extended resting periods when the SLR was fixed, where the highest thickness increment was observed in Bed 6 with an increment of approximately 13 cm.

Figure 2(a) shows the changes in the sludge deposit layer thickness under varying SLRs with a constant resting period of 6 days (Beds 1, 2, and 3), while Figure 2(b) shows the sludge accumulation under varying resting periods from 6 to 27 days at a constant SLR of 100 kg/$m^2$/year (Beds 2, 4, 5, and 6). Typically, the sludge deposit thickness was the highest whenever the raw septage was newly loaded. The sludge deposit lost its moisture via drainage or evapotranspiration during the resting period, resulting in the shrinkage of the sludge deposit that slightly reduced the sludge thickness. It was observed in Bed 1 and the early phases of Beds 2 and 3.

The thickness measurement was challenging when a prolonged surface ponding was formed, where a significant amount of solids suspended rather than settled on the bed surface. In addition, the turbulence created upon loading also scoured the existing sludge deposit layer and altered the thickness. Therefore, the thickness could only be measured based on the visible color difference between the ponding level and the sludge deposit layer, resulting in a significantly higher sludge thickness. The sludge deposit thickness in Beds 2 and 3 in the late phase was relatively high, leading to surface ponding during the resting period. In addition, due to the long rest time, the hydraulic loads of Beds 4, 5, and 6 are relatively large, resulting in a long period of water accumulation on the surface since the beginning of the experiment. Nevertheless, sludge shrinkage was still observed after full infiltration of raw sludge.

MC and TS content (TSC) of the sludge deposit are some of the important measurements for the STRB performance, as both parameters are required to meet the government regulation for solid sludge disposal (SPAN 2008). The MC needs to be dewatered below 80%, providing at least 20% of the TSC. Figure 3 illustrates the TSC% of the sludge deposit in each bed over the experimental period, and the average MC% and TSC% are summarized in Table 1. The TSC% of the sludge deposit in Bed 1 with 50 kg/$m^2$/year SLR and 6-day resting period were above 30%, averaging 34%. Although the SLR of 100 kg/$m^2$/year delivered slightly poorer dewatering, the average TSC% generally maintained above 20% and obtained an average of 23%. However, the thick sludge deposit in the late phase of the experiment led to surface ponding, resulting in high MC% and low TSC%. Bed 3 observed similar results when the SLR was increased to 150 kg/$m^2$/year. The high SLR significantly increased the hydraulic loads that require dewatering, and the sludge accumulation rate due to the SLR was also a crucial factor in the sludge dewatering efficiency.

**Table 1** | TS load, sludge deposit thickness (T) accumulation, average MC, TSC, and TVS/TS ratio in each STRB

| Bed | TS (kg) | Initial T (cm) | Final T (cm) | Increments (cm) | MC (%) | TSC (%) | TVS/TS ratio (%) |
|---|---|---|---|---|---|---|---|
| 1 | 2.29 | 7.33 | 7.50 | 0.17 | 66.29 ± 8.71 | 33.71 ± 8.71 | 30.55 ± 9.71 |
| 2 | 5.24 | 11.33 | 20.00 | 8.67 | 77.15 ± 10.56 | 22.85 ± 10.56 | 33.40 ± 9.16 |
| 3 | 6.87 | 11.00 | 20.83 | 9.83 | 76.37 ± 9.56 | 23.63 ± 9.56 | 36.19 ± 7.37 |
| 4 | 6.87 | 10.17 | 21.50 | 11.33 | 79.91 ± 11.09 | 20.09 ± 11.09 | 40.52 ± 6.73 |
| 5 | 8.83 | 10.67 | 22.00 | 11.33 | 87.25 ± 8.45 | 12.75 ± 8.45 | 35.87 ± 8.04 |
| 6 | 8.55 | 11.33 | 24.00 | 12.67 | 83.03 ± 9.88 | 16.97 ± 9.88 | 41.98 ± 8.34 |

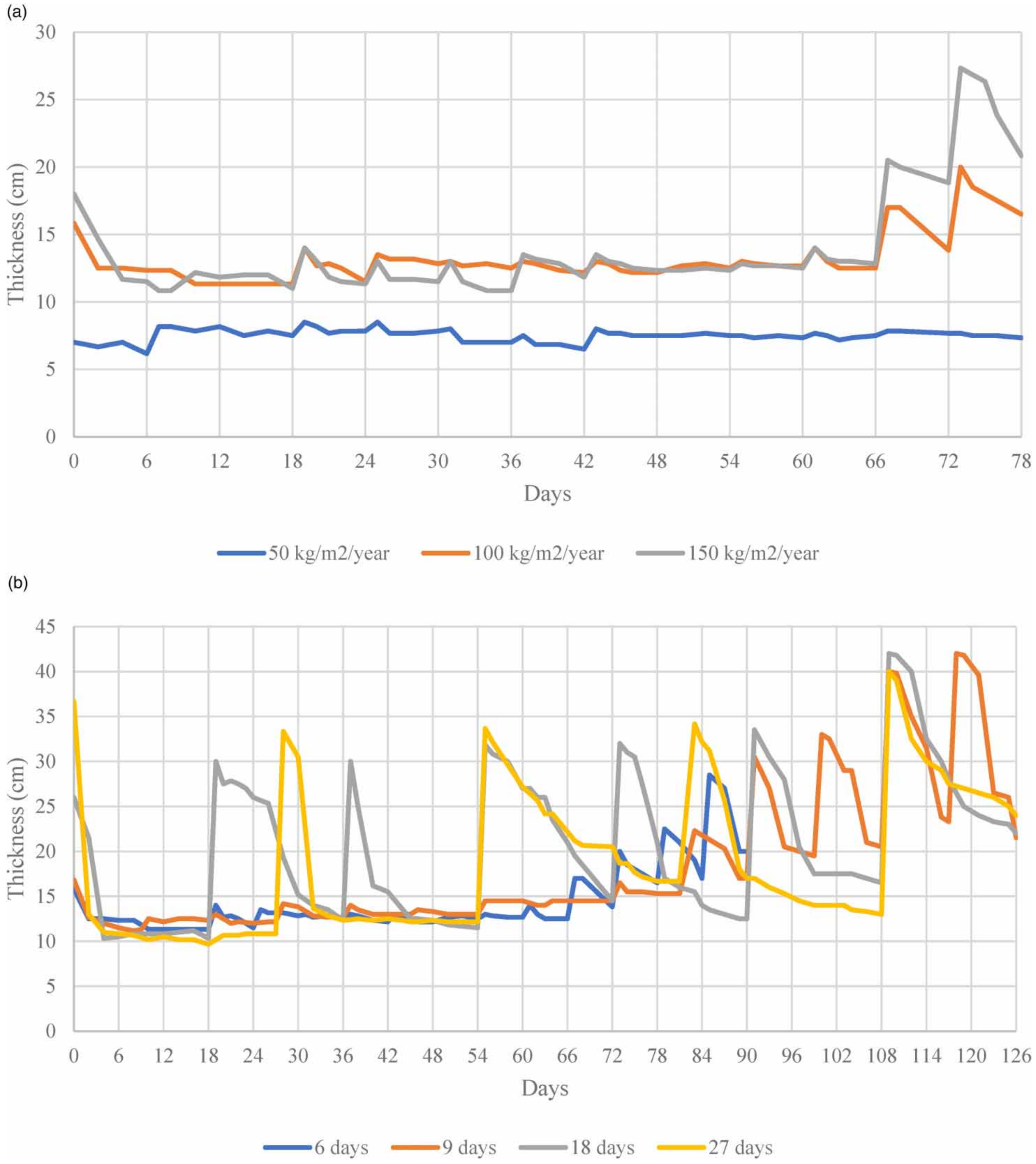


**Figure 2** | Sludge deposit thickness under varying (a) SLRs (with a 6-day resting period) and (b) resting periods (with an SLR of 100 kg TS/m$^2$/year).

No improvement in the dewatering efficiency was observed by extending the resting period from 6 to 27 days under the same SLR, which is similar to the findings in the literature (Kim *et al.* 2017). In general, the TSC% in beds with a resting period of 9 days or more failed to meet the minimum of 20%, where the average TSC% were 20, 13, and 17% for 9-, 18-, and 27-day resting periods, respectively. It is attributed to the large hydraulic loads and the excessive sludge accumulation

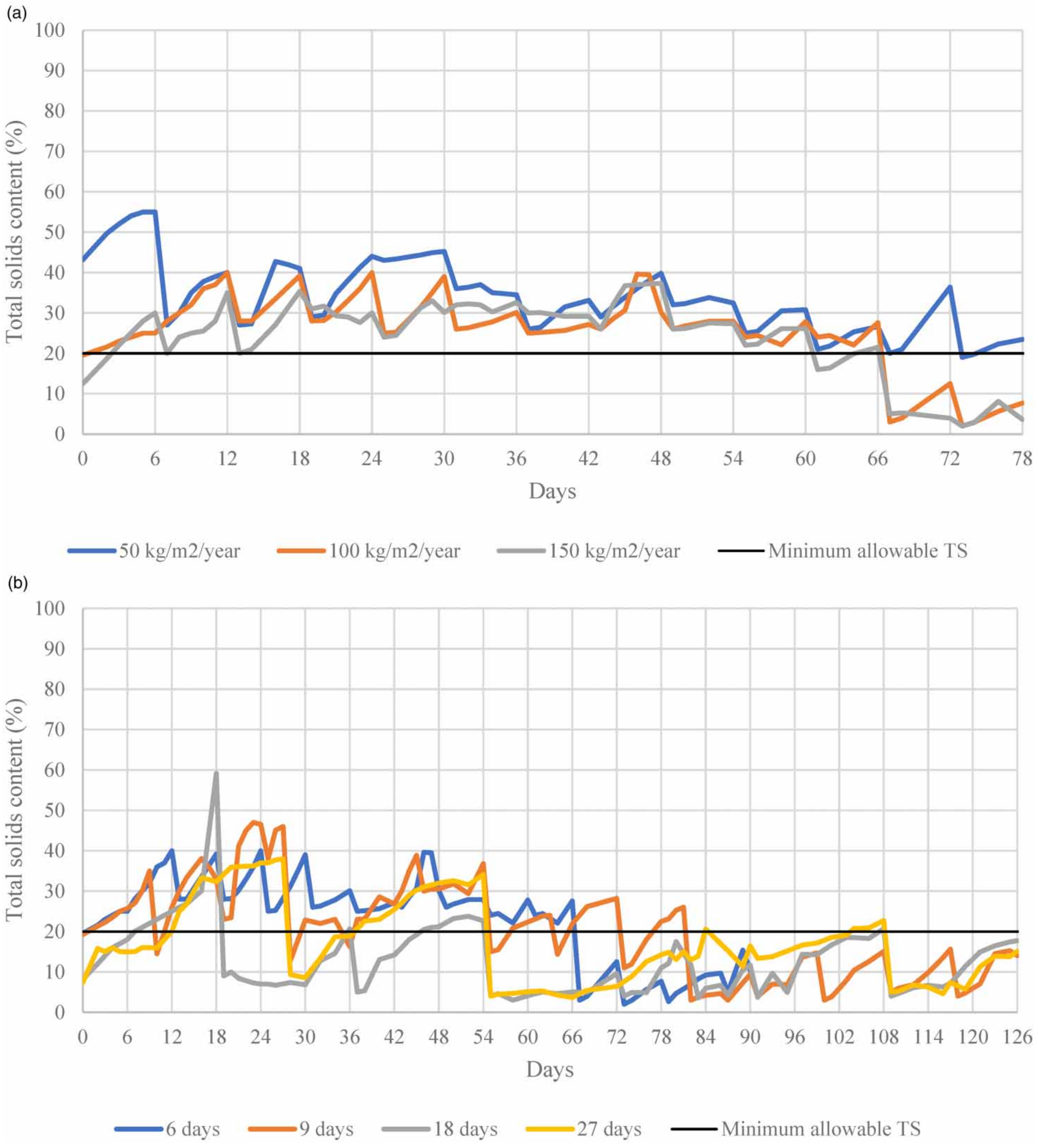


**Figure 3** | TSC under varying (a) SLRs (with a 6-day resting period) and (b) resting periods (with an SLR of 100 kg TS/m$^2$/year).

in these beds. The extended resting period results in higher hydraulic loads to the STRB during the feeding period, where a prolonged ponding was formed during the beginning phase of the resting period. The prolonged ponding has substantially reduced the permeability of the sludge deposit layer, resulting in a slow percolation rate and drainage dewatering. Hence, removing excessive sludge deposits is essential to avoid waterlogging in the reed beds.

The PL of the sludge deposit layers was determined to assess the minimum allowable MC% before permanent deformation. PL indicates the critical moisture that the sludge deposits begin to crack, leading to a portion of septage bypassing the sludge deposit layer (Tan *et al.* 2020). Figure 4 shows the PLs of the sludge deposit sampled from each bed. The PLs were similar across the beds, averaging 75 ± 2%. The average MC% of the sludge deposit in Bed 1 was 66%, approximately 10% below the PL. In Bed 1, the cracks on the sludge deposit were observed due to low MC, which allowed the raw sludge to bypass this low permeable layer and promote drainage dewatering. However, the severe crack condition would deteriorate the filtration efficiency and result in a poor quality of rejected water (Tan *et al.* 2020). Therefore, insufficient SLR and excessive resting periods are undesirable in the STRB for septage treatment, as the sludge deposit requires sufficient moisture to maintain the filtration performance (Trein *et al.* 2019).

On the other hand, the average MC% of the sludge deposit in Beds 2, 3, and 4 were slightly higher than the PL, and minor cracks could be observed in the sludge deposits during the last few days of the resting period. However, the cracks were covered by the newly formed sludge deposits in the subsequent loading cycle. No significant cracks were observable in these beds during the late phase of the experiment, as the thick sludge deposits led to prolonged surface ponding and high MC% in sludge deposits. Similar observations were found in Beds 5 and 6, but waterlogging occurred earlier than in Beds 2, 3, and 4 due to the high solid loads at a long resting period, resulting in a much higher average MC% in sludge deposits than PL.

Climate condition is regarded as a crucial factor in dewatering efficiency in STRBs (Stefanakis 2020). This study obtained key climatic data, including air temperature, relative humidity, wind speed, and precipitation from a weather station installed at Curtin University Malaysia. The data gathered on a daily basis are summarized in Figure S1. The climate condition in Miri, Sarawak, is a tropical rainforest climate, where the air temperatures were between 22 and 34 °C over the experimental period, and the average temperature was 27 ± 1 °C. The consistently high air temperature over the experimental period was conducive to the dewatering process in STRBs (Varma *et al.* 2021). In addition, the minimum and maximum relative humidity were 47 and 100%, respectively, while the average relative humidity was 87 ± 3%. The maximum wind speed recorded was 7.9 m/s, but the average wind speed was only 1.4 ± 0.5 m/s. Although several heavy rainfall events were recorded during the experiment, the effect of rainfall on the dewatering performance was excluded since the reed beds were located within the roof area. If the STRBs are exposed to rainfall, the MC% in the sludge deposits is expected to be much higher, and a longer resting period is required to dry the solids.

During the sludge stabilization, the volatile solids in the sludge deposit are degraded to low-hazardous bio-solids. Hence, the ratio of TVS/TS, known as the volatile solids fraction, is used to assess the sludge stabilization efficiency. Table 1 presents the average TVS/TS ratio in the sludge deposits sampled from each bed. The TVS/TS ratios ranged from 30 to 40% across the

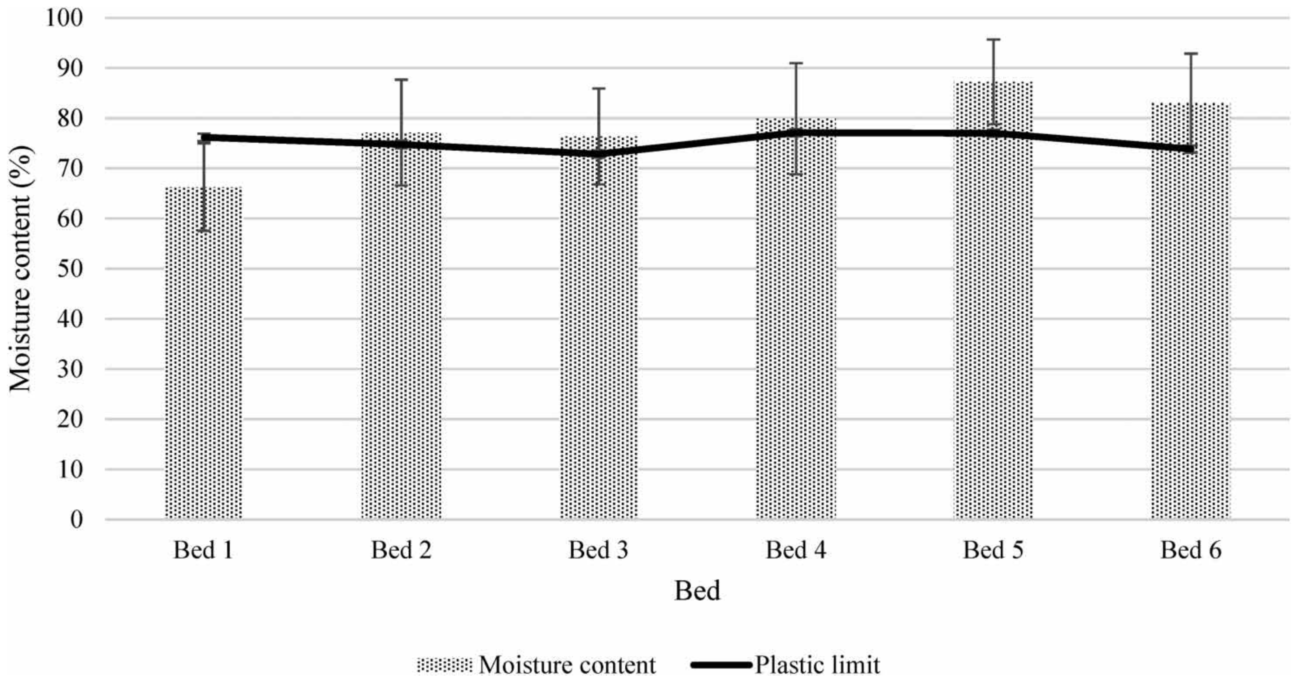


**Figure 4** | MC and PL of sludge deposit layer in each STRB.

beds. The increasing TVS/TS ratio was observed with the higher SLRs. The high solid loads lead to more particulate pollutants retained in the sludge deposit layer, which increases the amount of volatile solids for degradation (Wang *et al.* 2018). Under the resting period of 6 days, the SLR of 50 kg/m$^2$/year has the lowest TVS/TS ratio, with an average of 31%, indicating excellent sludge stabilization in the bed. Meanwhile, the average TVS/TS ratios were 33 and 36% when the SLR was increased to 100 and 150 kg/m$^2$/year, respectively. As mentioned, the excellent dewatering efficiency in Bed 1 results in severe cracking in the sludge deposit layer. This circumstance creates an oxygen-rich condition in the sludge deposit layer, promoting aerobic mineralization and accelerating the degradation of volatile solids (Leite *et al.* 2023). Therefore, the efficiency of sludge stabilization strongly depends on the dewatering performance.

The TVS/TS ratio showed an increasing trend with an extended resting period from 6 to 27 days. At the end of treatment, the average TVS/TS ratio was above 35% for beds operated with an 18-day resting period, and it exceeded 40% for 9- and 27-day resting periods. The prolonged surface ponding due to the large hydraulic load and excessive sludge accumulation in the beds operated with long resting periods hinders the oxygen exchange between the atmosphere and the volatile solids, limiting the sludge mineralization efficiency and leading to a high TVS/TS ratio (Cárdenas-Talero *et al.* 2022). Therefore, the MC% beyond the PL was determined to have a higher TVS/TS ratio, as shown in Bed 6, whereas Bed 1 with the lowest MC% was much lower than the PL and has been confirmed to have the lowest TVS/TS ratio.

### 3.3. Rejected water

Figure 5 shows an example of discharge flux measured from each reed bed with the same batch of raw septage. As STRBs were loaded in batches, the discharge of rejected water did not occur immediately upon the loading, but a delay of flow occurrence was observed. The delay duration is commonly used to describe the bed conditions, whether the STRB is normal, overdried, or ponded, which depends on the sludge deposit accumulation (Guo *et al.* 2022). When a low SLR and an extended resting period are provided, adequate drying in the sludge deposit leads to the formation of surface cracks, resulting in a fast discharge of the rejected water upon loading. However, the continuous accumulation of solids and organic matter increases the PL of the sludge deposit (Mohajerani *et al.* 2019), which fills the void spaces created by the cracking and reduces the layer permeability (Höfgen *et al.* 2019). Therefore, the flow delay could be varied depending on the bed situation. It was

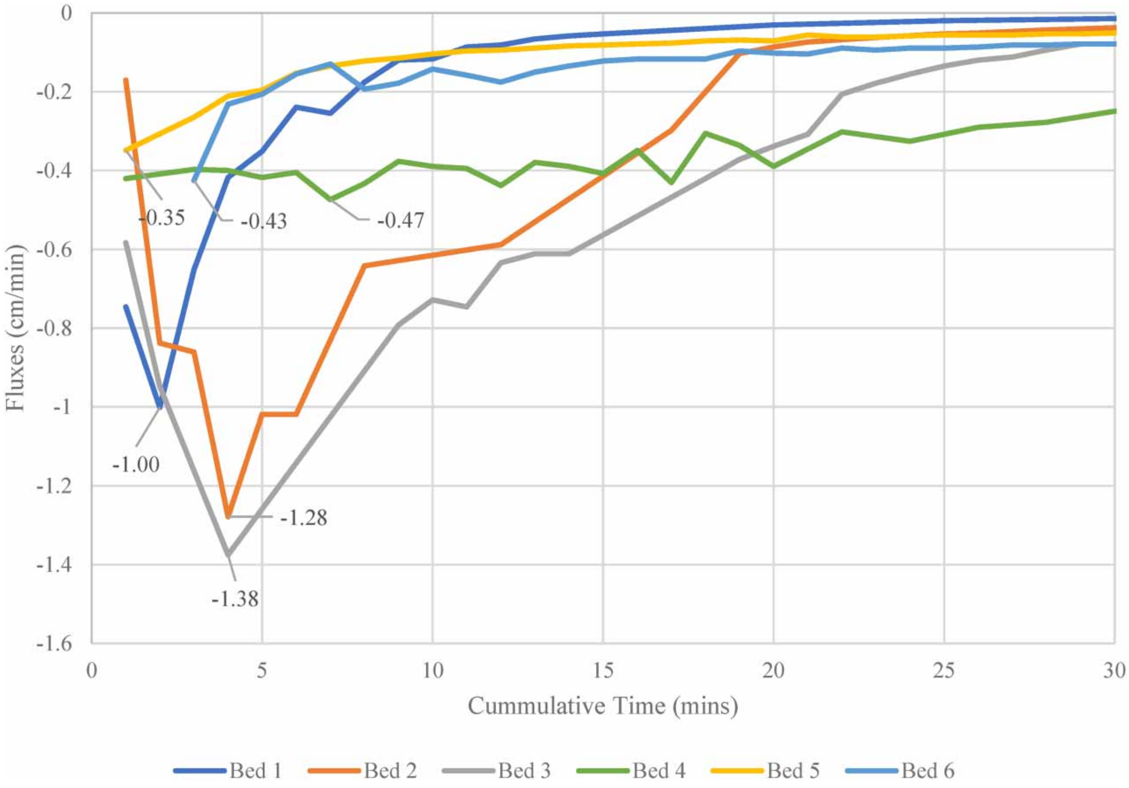


**Figure 5** | An example of discharge flux in each STRB under the same batch of raw septage (TS concentration = 10,800 mg/L).

observed in Bed 6 under an SLR of 100 kg/m$^2$/year with a resting period of 27 days, where the excessive sludge accumulation delayed the discharge flow occurrence compared to other cases. The longest delay recorded was found to be more than 3 h (180 min).

When the STRB was under overdried and normal conditions, the discharge flux reached a maximum rate at the beginning of the discharge, and it decreased over the rest period, as shown by the discharge fluxes of Beds 1, 2, and 3 in Figure 6. It is

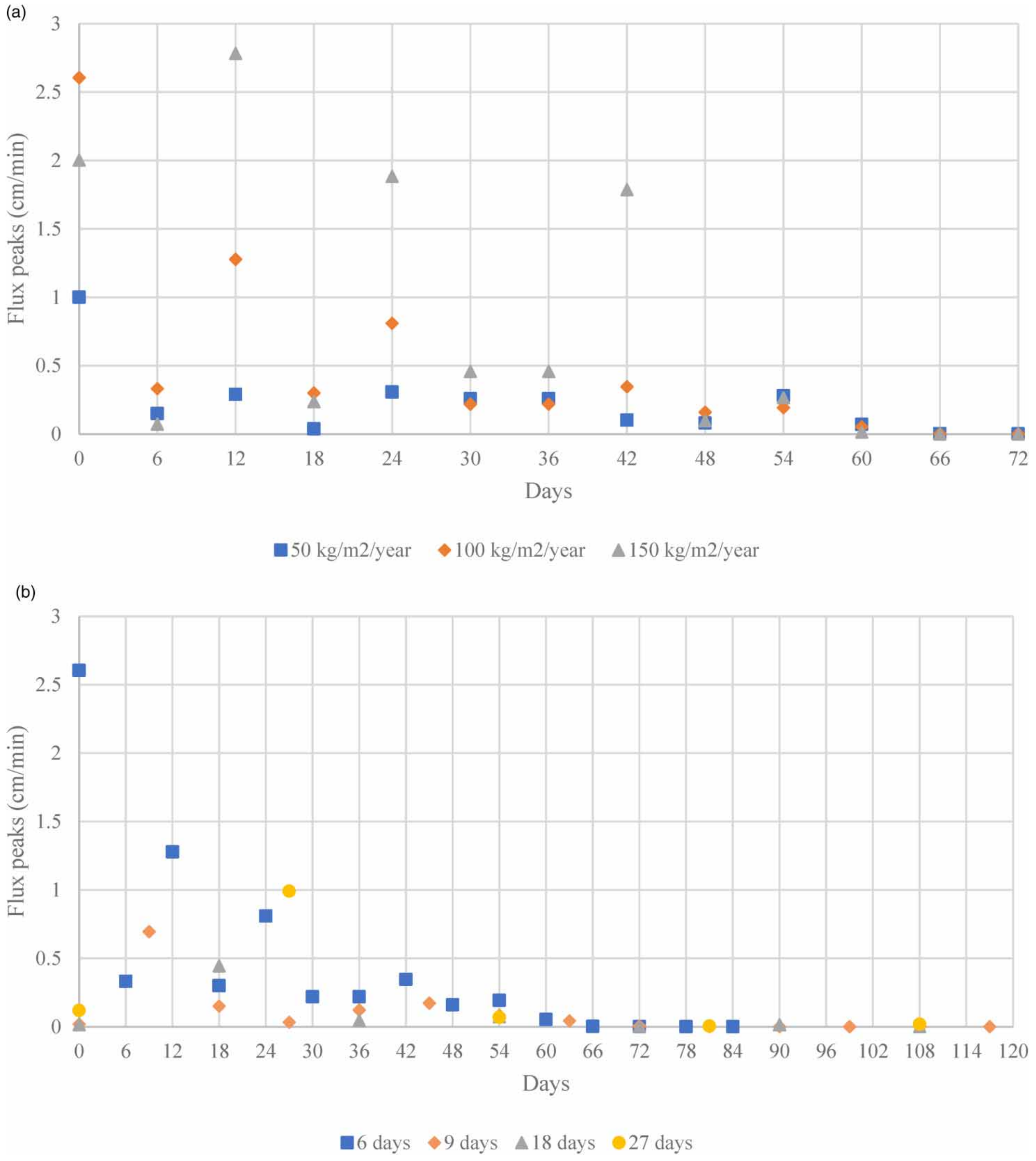


**Figure 6** | Flux peaks under varying (a) SLRs (with a 6-day resting period) and (b) resting periods (with an SLR of 100 kg TS/m$^2$/year).

because the hydraulic head is the main driving force of the water percolation through the substrate filters (Dirwai *et al.* 2021). In the beginning phase, the surface ponding at the top bed surface created a larger hydraulic head at the top bed surface, resulting in a higher peak flux (Huong *et al.* 2023). Nevertheless, the overdried sludge deposit in Bed 1 created a significantly high peak flux, and it sustained for a short period and decreased rapidly. When the sludge deposition was in a normal state, the peak flux lasted longer and then gradually slowed down, as observed in the discharge flux dynamics of Beds 2 and 3.

The increased hydraulic loading due to the higher SLR is also observed to accelerate the discharge flux. Based on the peak fluxes presented in Figure 6, the peak fluxes of Bed 3 were usually higher than Bed 2, while the peak fluxes of Bed 1 remained slow over the experimental period. It is because when a higher hydraulic load is applied, the deep surface ponding at the top surface creates a higher hydraulic head difference that results in a higher discharge flux (Huong *et al.* 2023). The discharge fluxes of Bed 2 were consistently higher than Bed 1 as the bed was operated under a higher SLR. However, the discharge flux in Bed 3 was slower than that of Bed 2 on several occasions, which was attributed to the more sludge deposit accumulation that reduced the permeability of the bed, resulting in a slower discharge flux (Tan *et al.* 2020). Therefore, the sludge deposit is an important factor in the drainage dewatering in STRBs.

The excessive sludge deposit accumulation has caused Beds 4, 5, and 6 to experience severe waterlogging problems with prolonged surface ponding. In these beds, the discharge fluxes of rejected water remained slow over the resting period. The extensive filling of void spaces within the sludge deposit layer ensured that the entity of the layer to act as a low permeable film to filter the rejected water (Kochetkov & Modin 2022). In addition, a decreasing trend of peak fluxes was observed in each STRB throughout the experiment, where the discharge fluxes of rejected water were slower than 0.5 cm/min in the late phase of experiments. It is attributed to the continuous sludge accumulation in the beds, in which the sludge deposit accumulation not only increased the deposit layer thickness but also compressed the layer, thus reducing the permeability and creating a higher flow resistance that limits water infiltration (Khomenko *et al.* 2019).

Table 2 presents the quality of the rejected water from each STRB. On average, the COD and TS concentrations in the rejected water were 190 ± 60 and 2,890 ± 1,960 mg/L, respectively, and the removal efficiencies were 96 and 88%, respectively. Although the quality of rejected water was still unable to meet the industrial effluent discharge standard, the excellent COD and TS removals still implied that the proposed STRB is a reliable septage treatment system (Jain *et al.* 2022). In addition, the average DO concentration was 6.3 ± 1.7 mg/L. The significant DO recovery revealed that the reed bed system could be effectively reaerated through the loading–resting cycle, subsequently promoting aerobic contaminant degradation (Wang *et al.* 2020). It was proven by the high $NO_3^-$ concentrations in the rejected water, where the average concentration reached 738 ± 396 mg/L, showing the prominent occurrence of nitrification in the beds. In addition, the average pH value of 7.1 is slightly lower compared to the pH of raw septage, which is attributable to the changes in chemical characteristics upon the nitrification–denitrification process (Gu *et al.* 2022).

Figure 7(a) and 7(b) present the COD and TS concentrations of the rejected water from each STRB, respectively. The COD concentrations were consistently low compared to the influent, which showed the excellent treatment capacity of STRBs for organic matter. The sludge deposits are essential in the STRB, which acts as a filter and biofilm to remove the contaminants in

**Table 2** | Quality of rejected water from each STRB

| | COD (mg/L) | TS (mg/L) | DO (mg/L) | $NO_3^-$ (mg/L) | pH |
|---|---|---|---|---|---|
| Raw septage | 4,776 ± 1,885 | 24,475 ± 14,919 | 0.24 ± 0.12 | 341 ± 105 | 7.94 ± 0.38 |
| Bed 1 | 223 ± 56 | 3,303 ± 2,137 | 5.74 ± 2.19 | 882 ± 409 | 6.83 ± 0.51 |
| Bed 2 | 206 ± 64 | 2,680 ± 1,851 | 6.56 ± 1.66 | 588 ± 356 | 6.80 ± 0.53 |
| Bed 3 | 173 ± 65 | 2,812 ± 1,950 | 5.59 ± 2.07 | 629 ± 309 | 6.97 ± 0.64 |
| Bed 4 | 240 ± 72 | 2,996 ± 2,032 | 6.43 ± 1.46 | 972 ± 482 | 7.28 ± 0.50 |
| Bed 5 | 124 ± 43 | 2,638 ± 1,909 | 7.17 ± 1.01 | 567 ± 323 | 7.18 ± 0.42 |
| Bed 6 | 171 ± 55 | 2,883 ± 1,855 | 6.53 ± 1.61 | 790 ± 497 | 7.43 ± 0.32 |
| Average | 190 ± 59 | 2,885 ± 1,956 | 6.34 ± 1.67 | 738 ± 396 | 7.08 ± 0.49 |
| Removal percentage | 96.03% | 88.21% | – | – | – |

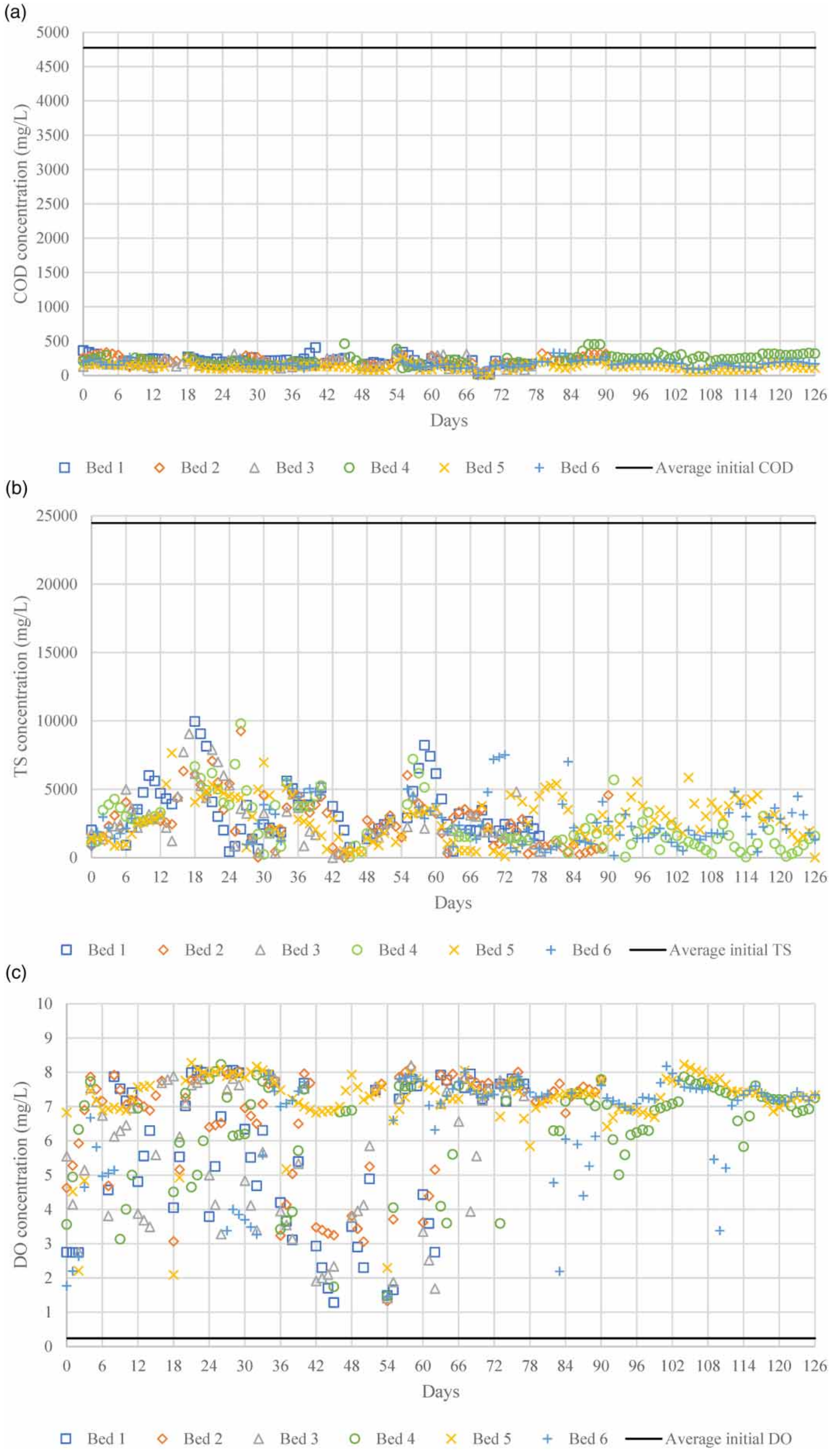


**Figure 7** | Concentrations of (a) COD, (b) TS, and (c) DO in rejected water from each STRB.

the septage. The low permeability is advantageous in prolonging the hydraulic retention time of the rejected water in the beds, increasing the interactions between the contaminants and the bacteria attached to the biofilms (Varma *et al.* 2021). As a result, the COD and nitrogen removal efficiency improved with slow percolation and low discharge flux. Table 2 shows that low COD concentrations were detected with STRBs observed with waterlogging issues, particularly in Beds 5 and 6. On the other hand, the cracks on the sludge deposit layer upon overdrying due to the low SLR have led to a fast percolation, where the raw septage bypasses the deposit layer through the preferential flow pathway, thus the retention time was insufficient to degrade the COD in the influent effectively (Khomenko *et al.* 2019). Generally, the TS concentrations were high at the early phase of the discharge, and the removal efficiency was better when the flux slowed down. The surface cracks allowed the solids to escape from the reed beds, which can be observed from the highest average TS concentrations in the rejected water of Bed 1, as well as the high TS concentrations during the early phase of the discharge. Nevertheless, when the incoming solids and organic matter filled the voids and compressed the sludge deposits, the TS concentrations in the rejected water dropped significantly since the filtration capacity was restored (Tan *et al.* 2017).

Figure 7(c) shows the DO concentrations in the rejected water from each STRB. In general, the DO concentration increased significantly in the rejected water, reaching around 8.0 mg/L in several cases. The high DO concentrations indicated good reaeration of STRB by installing ventilation pipes, which provide adequate oxygen exchange over the loading–resting cycle. In an oxygen-rich environment, the nitrogen cycle is dominated by nitrification, where ammonia ($NH_3$) is nitrified into $NO_3^-$. This explained the higher $NO_3^-$ concentration in the rejected water than in the influent. Nonetheless, the DO concentration decreased after the peaks in several events during the late phase of the resting period, and this is attributed to the waterlogging conditions, where prolonged surface ponding limits the oxygen restoration capacity in the beds (Yan *et al.* 2019).

The average effluent pH was between 6.8 and 7.4, indicating the neutral condition of the effluents. The neither acidic nor alkaline state of the effluent means that no additive is needed for pH adjustment, thus creating a chemical-free environment for nutrient decomposition. Results also revealed that the pH value of the effluents did not show a direct relation to the other effluent quality (Presti *et al.* 2021).

This study observed that the STRB operated with an SLR of 100 kg/m$^2$/year and a 6-day resting period, or an operation practice of 1.67 kg TS/m$^2$ per loading, delivered a promising performance in sludge dewatering and stabilization, as well as a good rejected water quality. By assuming the TS content of raw septage as 3%, the loading volume is approximately 55 L/m$^2$. According to the Malaysian Industry Guidelines (SPAN 2008), the septage production in a household with five population equivalents is 200 L/year. Since a mandatory desludging of septic tanks in household areas every 4 years is implemented in Sarawak (Leong *et al.* 2022), the sludge volume removed is estimated at 800 L. As a result, a 15 m$^2$ reed bed is needed to treat the septage removed from the household septic tank. The reed bed can operate for 60 cycles in a year; thus, the required area of the reed bed for each household is 4 m$^2$ since the desludging is only conducted every 4 years. In urban areas, the large land area requirements of the STRB may increase capital expenditures, but it is an economic solution for the rural areas where the land availability is not an issue.

High variability in septage properties is crucial to the consistency of sludge dewatering and treatment performance in STRBs (Tan *et al.* 2023). According to the literature, the raw septage collected in this study was classified as low-strength due to the relatively low TS and COD concentrations (Zewde *et al.* 2021). This can be attributed to the regulation of the Sarawak government on mandatory desludging of septic tanks in household areas every 4 years to prevent excessive sludge accumulation in the septic tank (Leong *et al.* 2022). Since SLR is used as the operation practice of STRB, the loading volume could be large when the septage is collected from households with a low utilization rate. Raw septage with a low TS concentration is less likely to deteriorate the dewatering and treatment performance, but the freeboard of the STRBs must be designed with adequate capacity to cater for the loading volume (Tan *et al.* 2020). In contrast, the septage removed from the septic tank with a low desludging frequency is expected to have high TS and COD concentrations, and it could be a concern as the literature has reported that the high organic fraction in the solids leads to poor sludge dewaterability (Haddis *et al.* 2020). Therefore, a longer resting period is needed for such a high-strength septage to ensure sufficient dewatering and stabilization. In addition, further research on the rejected water quality when treating high-strength septage is necessary.

In conclusion, this study gains important insights into the sludge deposit buildup in STRBs, where a high SLR increased the sludge deposit accumulation rate and deteriorated the dewatering and stabilization efficiency. At the same time, the influence of the resting period was less significant. Nevertheless, the experiment can be improved by further investigating the mechanisms of sludge deposit buildup, as it is the main cause of the drainage dewatering reduction. The varying septage properties, particularly the TS content, complicate the estimation of sludge accumulation, thus affecting the consistency of the results. Also, more repetition of the laboratory reed beds under the same operation practices is recommended to monitor the variance of sludge accumulation rate.

## 4. CONCLUSION

The accumulation of sludge deposits on the STRBs affected the overall dewatering efficiency. The reduction in effective porosity and permeability of the sludge deposit layer increased the specific flow resistance, thus decreasing the dewatering performance. The high SLRs and prolonged resting periods required additional hydraulic loads, leading to waterlogging conditions that have hindered the oxygen reaeration into the sludge deposit layer. In such a circumstance, the treatment duration increased, resulting in better filtration but less-efficient sludge stabilization. This study revealed that the STRB operated with an SLR of 100 kg/m$^2$/year and a 6-day resting period performed the best in sludge dewatering and stabilization. Under such conditions, the final TSC was 23%, which met the government regulation for solids disposal. In addition, the MC of the sludge deposit was within its PL, which avoided the occurrence of severe cracks that deteriorated the treatment performance. The low TVS/TS ratio of 33% also indicates desirable sludge stabilization. All STRBs were capable of delivering an average of 96 and 89% for COD and TS removals, respectively. However, results showed that inadequate SLRs and resting periods could lead to crack conditions on the sludge deposit layer, leading to rejected water bypassing the substrate filter and eventually resulting in higher COD and TS concentrations in the rejected water. The promising oxygen restoration in the STRBs also promotes aerobic nitrification that improves rejected water quality. The experiment can be improved by further investigating the mechanisms of sludge deposit buildup, where more repetition of the laboratory reed beds is recommended to monitor the variance of sludge accumulation rate under the same operation practices.

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## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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