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Septage Treatment Using Vertical-Flow Engineered Wetland: A Critical Review

Yee Yong Tan*[a], Fu Ee Tang[a], Agus Saptoro[b], Ee Huey Khor[b]

[a]Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Sarawak, Malaysia
[b]Department of Chemical Engineering, Faculty of Engineering and Science, Curtin University Sarawak, Malaysia
tan.yee.yong@postgrad.curtin.edu.my

Septage, which is a mixture of sludge, scum and liquid, is a type of faecal sludge that is specifically removed from an individual septic tank. Their biochemical stability and high concentration of solids and nutrients are the major technical challenges towards effective treatments in the existing wastewater treatment systems. A subsurface vertical-flow engineered wetland (VFEW) is, therefore, introduced as a feasible decentralized septage treatment option for small or medium communities due to its abilities in achieving excellent treatment and energy efficiency and reasonable cost through a simple operation. In general, the VFEW removes suspended solids, organic matter and nitrogenous components constituted in raw septage efficiently and sustainably. This paper presents a critical review on the state-of-the art of septage treatment using vertical-flow engineered wetland with regards to their characteristics and operation. The system-factor such as substrate profile and operational factors such as solid loading rate (SLR) and frequency of loading have been generally agreed as major factors governing the effectiveness of VFEWs. The selection of substrates is crucial to ensure a long-term usability of the VFEW with regards to the clogging phenomenon. The SLR, which ranged from 30 to 250 kg TS m^{-2} y^{-1}, is of great importance to the treatment capability. The frequency of loading determines the rate of oxygen renewal, microbial growth and mineralization of the accumulated sludge deposit within the VFEW system. Future research directions and recommendations are also outlined.

1. Introduction

In Sarawak, the individual septic tank (IST) is the main sanitation system used in both the cities and rural areas. Lau (2012) reported that there are more than 370,000 ISTs in the entire state, serving approximately 1.9 million people. In ISTs, massive amounts of recalcitrant solids are generated as by-product during the treatment process, subsequently reducing the space for biological degradation and ultimately leading to the discharges of untreated sewage or minimally-treated sewage (Hamersley et al., 2001). Therefore, a regular desludging is necessary to maintain the treatment efficiency of ISTs. During desludging, septage, which is a semiliquid mixture of sludge, scum and liquid, is pumped out from the IST. It constitutes an extremely high concentration of solids and nutrients, which can be 10-100 times higher than municipal wastewater (Kone and Strauss, 2004). Moreover, septage shows low biodegradability due to its long retention time in the IST, subsequently hampering the efficiency in treating it with the existing wastewater treatment system (Paing and Voisin, 2005). As a result, the development of septage treatment facilities in developing countries is unappreciated compared to sewage treatment (Kone and Strauss, 2004).

In Sarawak, there are only three conventional centralized septage treatment systems located in the urban areas of Kuching, Miri and Sibu (Sewerage Services Department Sarawak, 2014). Similar to the sewage sludge treatment, such conventional septage treatment method is more expensive and troublesome compared to the wastewater treatment (De Filippis et al., 2013). In addition to this, proper septage management is still absent in the less densely populated rural areas. Land application is the simplest

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alternative to the septage management in these areas, but the unplanned disposal of septage could be a risk to spreading of disease-causing pathogens and environmental pollution.

The subsurface vertical-flow engineered wetland (VFEW) is introduced as a feasible decentralized septage treatment option for small or medium urban or rural communities due to its advantages of potentially achieving excellent treatment and energy efficiency, reasonable cost, and simple operation (Liénard et al., 1995). The VFEW is an artificial wastewater treatment system incorporating substrate, vegetation and the microbial community to purify contaminated water via biological, chemical and physical processes. In such systems, the influent is loaded to the surface of the wetland bed, then percolating vertically through the substrate towards the drainage system. In general, the VFEW is operated intermittently, where the system is only loaded after the previous batch of influent has been completely drained. This wet-dry cycle leads to a variably-saturated condition and creates a "temporal redox variation" to reaerate the wetland bed (Langergraber, 2008). Such technology has been widely applied to treat various types of wastewater such as municipal sewage, agricultural wastewater, leachate and storm water, but its application in septage treatment is relatively less common.

In earlier attempts, the VFEW aimed to dewater and consolidate the sludge-type wastewater instead of removing the constituted pollutants (Kadlec and Wallace, 2008). Recently, the VFEW system has become an attractive option towards septage treatment due to its excellent removal of total suspended solids (TSS), organic matter and nutrients (Koottatep et al., 2001). In order to give an insight to the pros and cons of such applications, a review of several VFEW-based septage treatment systems with regards to their features, operational strategy, and performance is presented in this paper. The relation between the treatment performance and the system-related and operation-related factors, including substrate profile, solid loading rate (SLR), and frequency of loading are discussed.

2. Literature Surveys

Lienard and Payrastre (1996) constructed a pilot-scale two-staged VFEW system to treat septage collected from domestic households, which is recognized as the first systematic study about the treatment performance of VFEW-based septage treatment system. The first stage of treatment, which consisted of two gravel beds with a surface area of 0.6 m^2, was targeted at filtering the solid constituents within raw septage. The substrate was mainly constructed by coarse gravel with a thickness of 0.25 m. The top of the substrate was vegetated with common reeds (*Phragmites australis*) and a set of ventilation pipe was installed to aerate the lower part of the substrate. At this stage, the wetland beds were loaded with raw septage at a loading rate of 1.5 m^3 wk^{-1}, demonstrating an approximate solid loading rate (SLR) of 70 kg TSS m^{-2} y^{-1}. Particulate constituents were accumulated on the surface of the wetland beds, forming a layer of sludge deposit. With the aerated substrate, the aerobic biological treatment processes were promoted, subsequently achieving a removal efficiency of 70 % for chemical oxygen demand (COD), 79 % for total Kjeldahl nitrogen (TKN) and 66 % for ammonia nitrogen ($N\text{-}NH_3$). This stage of treatment operated smoothly, where the clogging phenomenon was not reported in this study.

The second stage wetland consisted of four parallel wetland beds, each bed with a surface area of 0.1 m^2. At this stage, the aim was to enhance the removal of organic matter and nutrients through stimulating bio-chemical mechanisms. The bottom of the bed was partially exposed to the atmosphere. In order to prolong the hydraulic retention time, a 0.20 m thick sand layer was placed at the top of the gravel substrate. The wetland bed received the percolate discharged from the first stage treatment at a rate of 1 dose d^{-1}. The study indicated that the treatment efficiency at this stage depended upon the thickness of the gravel layer. A 0.60 m depth of substrate could deliver a good quality effluent with low concentration of COD (≈150 mg L^{-1}) and $N\text{-}NH_3$ (< 1 mg L^{-1}).

This type of two-staged VFEW system has been developed into a full-scale treatment plant, Beaumont-la-Ronce, to treat raw septage in the rural area in France (Paing and Voisin, 2005). The first stage treatment comprised of 6 parallel wetland beds with a total surface area of 612 m^2. At this stage, the substrate was constructed by gravel with a depth of 0.90 m. The common reed was selected as wetland vegetation and a set of ventilation pipes was installed. In this treatment plant, pre-treatment was provided to screen large gross solids constituted in raw septage. Then, the raw septage was homogenized through a stirring process. The system was operated continuously for seven days, where the influent was separated to four batches of feeding (5 m^3 per batch). Then, the wetland beds were rested for 5 weeks after the 7-day operation. The applied SLR in this plant was 46 kg TSS m^{-2} y^{-1}. The first stage treatment resulted in a high removal rate for suspended solids (99 %), BOD_5 (98.5 %), COD (98.5 %), TKN (94 %) and total phosphorus (94 %). Nevertheless, the concentration of nitrate ($N\text{-}NO_3^-$) increased after treatment. The physical filtration on the accumulated sludge deposit layer was regarded as the main removing mechanism at this stage, but substrate clogging was not observed throughout the operation due to the existence of stem and root systems of wetland vegetation.

The second stage treatment consisted of 3 parallel wetland beds, which were constructed by 0.50 m gravel and 0.40 m top sand layer. The configurations and operating strategy were similar to the first stage treatment but an additional ventilation pipe was installed at the middle of substrate to promote the aerobic biological removing mechanisms. The second stage treatment produced considerable removal performance for TSS (63 %), BOD (65 %), COD (48 %) and TKN (72 %).

In Thailand, Koottatep et al. (2001) proposed a single-staged VFEW system for septage treatment, which was regarded as the first published study in the tropical region. Three pilot-scale wetland beds were constructed, where each bed had a surface area of 25 m^2 and a depth of 0.65 m, which was constructed by a 0.10 m sand layer and 0.55 m gravel layer. The narrow-leaf cattail (*Typha augustifolia*) was the wetland vegetation used in this system. A bar screen was provided to remove the gross solids within the raw septage. A set of aerated pipes was installed to promote the growth of vegetation. Under the warm and humid tropical climate conditions, the bio-chemical processes are observed with a higher efficiency due to the active microbial community. Therefore, a higher SLR is possible can be applied in these areas compared to those in the temperate regions. Several SLRs were investigated, ranging from 80 to 500 kg TS m^{-2} y^{-1}. The experimental results showed that the SLR of 250 kg TS m^{-2} y^{-1} produced the highest treatment efficiency, with a loading frequency of once or twice a week. On average, this VFEW system removed more than 80 % of TS, COD, TKN and $N\text{-}NH_3$ under the optimum SLR. The concentration of $N\text{-}NO_3^-$ increased significantly throughout the experiment. Nevertheless, the authors observed the poor growth of wetland vegetation due to the shock loading and water deficiency. As a result, the operation strategy was modified, where the wetland bed was impounded up to 6 days to yield a healthy growth of wetland vegetation. The occurrence of substrate clogging was not mentioned in this study.

After gaining experiences for seven years, Koottatep et al. (2004) concluded that a SLR of 250 kg TS m^{-2} y^{-1} provided sustainable treatment efficiency in tropical region. In addition to this, it was observed that a longer impounding period showed better performance in removing total nitrogen, but no significant effect upon the treatment of suspended solids and organic matter. A period of acclimatization should be provided in order to secure the growth of wetland vegetation. Panuvatvanich et al. (2009) further elaborated the positive impact of prolonging the impounding period in terms of stimulating denitrification. Additionally, this study suggested that increasing the thickness of sand layer might improve the removal efficiency of TN.

In Cameroon, Kengne et al. (2009) applied the same substrate profile and operating regime as in Koottatep et al. (2001) to dewater and treat faecal sludge collected from septic tanks and pit latrines. This pilot-scale wetland bed had a surface area of 1 m^2 and was vegetated with *Echinochloa pyramidalis*. This study verified that a SLR of 100 – 200 kg TS m^{-2} y^{-1} ensured high dewatering efficiency. A SLR higher than 200 kg TS m^{-2} y^{-1} may easily lead to substrate clogging. The dry matter content of biosolids can be higher than 30 % after treatment. The removal efficiency achieved by the system was 77 % for $N\text{-}NH_4^+$, 86 % for TSS, 90 % for TS, 90 % for TKN and 95 % for COD. Moreover, more than 100 t of dry plants and biosolids were produced in per hectare of wetland bed, which could be reused as fertilizer under proper management.

Troesch et al., (2009) designed and constructed a pilot-scale VFEW system to treat septage at a SLR of 30 kg TSS m^{-2} y^{-1}, which was low compared to the systems mentioned above. The substrate had a thickness of 0.55 m, which was mainly constructed by gravel. Two types of top layer were investigated in this study, which were sand layer and vegetal compost layer. The common reed (*Phragmites australis*) was vegetated at the top of the substrate. The raw septage was loaded either direct application or mixing with aerated sludge. The loading regime of mixing with aerated sludge could enhance the dewaterability of influent due to the flocculation caused by the chemical pre-treatment. The experimental results revealed that the concentration of TSS, COD and TKN reduced significantly, but the system still performed under expectation. The wetland bed covered with the sand layer produced a noteworthy sludge deposit layer at a rate of 11.5 cm y^{-1}. Nevertheless, the low applied SLR and appropriate resting period reduced the risk of substrate clogging. An operating regime of 2 – 3 days operation followed by 15 – 20 days resting was suggested to prolong the system lifetime. Vincent et al. (2011) elaborated that a 5–day feeding period and a 24-day resting period produced optimum treatment efficiency, and the SLR can be increased to 50 kg TSS m^{-2} y^{-1}.

Jong and Tang (2014) designed and constructed a pilot-scale two-staged VFEW-based septage treatment system in Sarawak, Malaysia. The design principle is similar to Lienard and Payrastre (1996). The first stage treatment consisted of three wetland beds, each bed had a surface area of 2.2 m^2. The substrate was constructed by 0.80 m of coarse gravel and was vegetated by the common reed (*Phragmites karka*). The wetland bed was loaded weekly at a SLR of 250 kg TS m^{-2} y^{-1}. At this stage, the results showed that the influent was significantly oxidized, and excellent removal rate for COD (96 %), $N\text{-}NH_3$ (87 %) and TSS

(97 %) was obtained. The second stage consisted of four wetland beds, each bed had surface area of 0.24 m^2, where the substrate was constructed by gravel, palm kernel shell and sand and was vegetated with either common reed or red button ginger (*Costus Woodsonii*). Two hydraulic loading rates were investigated at this stage, which were 0.0875 m d^{-1} and 0.175 m d^{-1}. The dosing was further divided into a frequency of 4 times or 8 times d^{-1}, and impounded for a day (Jong and Tang, 2014). The results reflected that a lower HLR can yield removal rates up to 95 % for COD, 99 % for $N\text{-}NH_3$, 79 % for organic nitrogen, 80 % for total nitrogen, and 98 % for TSS. Moreover, the lower dosing frequency might improve the removal rate. Nevertheless, the removal of $N\text{-}NO_3$ was still less desirable.

3. Critical review and discussion

In general, the VFEW provides excellent performance in removing TSS, COD, and TKN constituted in raw septage. Its simple construction and operation imply a huge potential to be a feasible decentralized septage treatment facility in less populated rural areas, especially in the tropical region. Up to now, most of the attempts still remained at experimental level. The current experiment outcomes showed positive results with regards to the efficiency and sustainability. Nevertheless, the development is hampered due to the absence of a complete design guideline. Based on the literature, it reflected that the system factors such as substrate profile and operational factors such as applied SLR and frequency of loading are of great importance to the performance of a VFEW-based septage treatment system.

3.1 System Factors

The substrate supports the growth of wetland vegetation, as well as acting a porous medium for physical filtration and bio-chemical reaction. Therefore the design of substrate is crucial to the hydraulic retention time of influent within the system, eventually dominating the removal efficiency. Besides, attention should be paid to the high solid contents in raw septage. Typically, coarse gravel was used to avoid clogging and ensure the long-term operation of VFEW. Based on the system mentioned above, the overall substrate thickness ranged from 0.25 m to 0.9 m. The influence of varying thickness of substrate has not been substantially covered in the literature with regards to the performance of septage treatment. As for the wastewater treatment, Torrens et al. (2009) observed that a thicker substrate has prolonged the hydraulic retention time of influent within substrate, which enhances the contact time between pollutants and microbial communities, ultimately improving the quality of effluent. Most of the existing studies focus on variation of the substrate materials such as sand, vegetal compost and palm kernel shell to improve the removal efficiency in septage treatment. Several VFEWs adapted a sand layer at top of the substrate to increase the filtering ability and to prolong the hydraulic retention time, especially in the second stage treatment of the two-staged VFEW system.

Besides, the selection of wetland vegetation and the degree of pre-treatment contribute a certain influence to the system performance. The most important role of wetland vegetation is to prevent the occurrence of substrate clogging by creating water flow paths in the upper layer of substrate through their root systems (Molle et al., 2006). In addition to this, the existence of vegetation is beneficial in enhancing the removal of water and contaminants via transpiration and nutrient uptake. The common reed (*Phragmites australis/ Phragmites karka*) is the most common vegetation used in VFEW-based septage treatment system. The degree of pre-treatment is crucial in reducing the risk of clogging. The implementations of pre-treatment, which can be physical or chemical, efficiently remove large particulate substances constituted in raw septage. A bar screen is found to be a common device to preliminary eliminate “rags and large objects” from entering the wetland system (Tchobanoglous et al., 2003).

3.2 Operational Factors

Instead of controlling the hydraulic load, the limitation of solid load is more practical to ensure the treatment capability and system durability. The operating regime with controlled SLR tackles the problem caused by the fluctuating characteristics of septage between each batch of collection. The particulate components were trapped on the surface of substrate, subsequently forming a layer of sludge deposit. This sludge layer with low permeability gradually reduces the infiltration capacity, ultimately leading to a permanent surface ponding and system failure, which is known as the phenomenon of substrate clogging (Hua et al., 2010). The formation rate of such low permeable top layer is proportional to the applied SLR. Although the experimental results have indicated that a low SLR yielded a better system sustainability and removal efficiency, it simultaneously limited the treatment capacity of the particular system. However, the optimum SLR for VFEW-based septage treatment system is still lack in literature. The SLRs applied in temperate region normally ranged from 30 to 70 TSS m^{-2} y^{-1}. Nevertheless, the SLR can up to 250 kg TS m^{-2} y^{-1} in tropical region, which demonstrates an outstanding performance (Koottatep et al., 2004).

The frequency of loading, which governs the interaction between SLR and resting period, appears to be a key operating strategy to achieve desirable removal efficiency. The VFEW system is loaded intermittently, where the system will be 'rested' after operating for a certain period. Such feeding-resting cycle stimulates oxygen renewal and promotes microbial growth and mineralization of organic residual. A high frequency of feeding is favourable in controlling the hydraulic retention time, but the associated short rest period is disadvantageous to the system re-aeration and dewatering of sludge deposit layer (Molle et al., 2006). Normally, the resting period is at least twice of the feeding period. In fact, the frequency of loading is not designed based on the optimum removal efficiency, but depend upon the simplicity of operation. A weekly-based feeding regime is an attractive approach due to its convenience in scheduling and sufficient resting period.

The VFEW is typically recognized as an aerated system that achieves excellent removal for BOD, COD and N-NH_4^+. Nevertheless, the dominating aerobic condition restrains the anaerobic processes such as denitrification, which results in high N-NO_3^- concentration within the effluent. Therefore, it is suggested to impound the influent in the wetland bed for a certain period to create a saturated condition, eventually promoting denitrification. Such operating regime has been found to be effective in decreasing the concentration of TN (Jong and Tang, 2014). The impounding of influent prevents the water deficiency in the system to secure the growth of vegetation (Koottatep et al., 2001).

3.3 Future research directions

To date, current studies have given useful insights in terms of substrate design, SLR and basic loading cycle to varying environmental condition. Nevertheless, a systematic design standard guideline of VFEW-based septage system is not yet established. The scale and capacity of the treatment are still designed based on rules-of-thumb, and the operational strategies are optimised according to a series of experiments. The treatment capability of VFEW-based septage treatment system is a result of biological, chemical and physical processes, which occurs actively with regards to the system itself and its operation. Therefore, the system configuration and associated operating regime requires customization to suit the surrounding environment and septage characteristics. However, the current knowledge in this field is still insufficient to establish a design guideline to provide design parameters.

Practical design tools such as mathematical models should be developed in order to ensure the efficiency of a particular VFEW system. The first-order kinetics model has been found to be less efficient in terms of design due to its limitation of site-specification and lacking in quantification of process and varying operating regime. A process-based model is more favourable since it provides a more comprehensive scheme towards the complex interactive processes under a variety of circumstances, which has become a state-of-art in the modelling and design of EW system. Up to now, several integrated models such as Hydrus-CW2D (Langergraber and Šimůnek, 2005) have been developed to simulate the hydraulic flow and treatment kinetic of the VFEW system. However, these existing models are limited to the application of municipal wastewater treatment, and a specific model for septage-based treatment is still absent. A feasible numerical model for septage-based treatment should include the consideration of high solid-content influent, clogging problem and dewatering efficiency.

4. Conclusions

The VFEW has become an attractive option in septage treatment due to its simple construction and operation. The studies have indicated that the VFEW performed well in removing TSS, organic matter and N-NH_4^+. The design of substrate profile and the management of feeding strategy are of great of importance in contributing towards an efficient and sustainable treatment performance. In terms of feeding strategy, the control of SLR and frequency of dosing is crucial, where both design parameters govern the increasing rate of accumulated sludge deposit layer and the renewal rate of oxygen within the substrate. However, all such design parameters are still decided based on rules-of-thumb. The current contribution in the literature is still insufficient to establish a comprehensive design guideline for the VFEW-based septage treatment system. Thus, the modelling of a particular system configuration and operation regime is crucial to determine the system performance, with variation in influential parameters, subsequently establishing useful knowledge towards ensuring its efficiency and sustainability.

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