Dewatering and Mineralization of Sludge in Vertical Flow Constructed Wetlands: A Review

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Abstract. Sludge treatment in vertical flow constructed wetlands (VFCWs) is a promising alternative to conventional treatment, which provides adequate treatment at low-cost, while being energy efficient. They may dewater and mineralize various kinds of sludge, including surplus sludge from activated sludge systems, agricultural slurries, and septage and faecal sludge effectively. This paper presents a review of the state-of-the-art of VFCWs treating sludge. The effects of varying design and operational parameters, as well as environmental factors on treatment performance are discussed. The paper also summarizes the performance of various pilot- and full-scale systems in terms of final dry matter content and degree of mineralization. In order to understand the governing processes and predict its performance, modelling of VFCWs in sludge treatment is suggested.

1. Introduction
The handling and treatment of sludge is a major issue around the world. This is mainly attributed to the massive generation of sludge as by-product from wastewater treatment plants (WWTPs) or onsite sanitation system such as septic tanks. Moreover, sludge management can be a complicated process which requires specialized technical expertise [1]. Approximately 60% of the total operational cost of conventional WWTPS are usually contributed to managing sludge [2]. Sludge treatment operations primarily involves two main processes, namely (i) dewatering, and (ii) stabilization. The aim of the dewatering process is to reduce sludge volume, subsequently increasing total solids (TS) content in the final sludge to reduce operational cost (i.e. handling, transportation and disposal). On the other hand, stabilization of sludge is aimed at stabilizing the biodegradable fraction of organic matter in sludge, by decreasing the organic fraction in solids (i.e. volatile solids (VS) content).

The philosophy of sludge management in conventional sludge treatment processes relies on building extensive collection and transport systems to treat it in a centralized facility. This creates problems for rural areas that utilizes small WWTPs or on-site sanitation systems such as septic tanks, which usually do not implement their own sludge treatment line, but instead transports raw sludge to larger WWTPs or sludge treatment facilities. For this, the decentralized subsurface vertical flow constructed wetland (VFCW) system may be considered for sludge treatment.

VFCWs for sludge treatment are also known as sludge treatment wetlands (STWs), and represent the state-of-the-art solution to sludge treatment with the vast majority existing and operating in various...
European countries since the late 1980s [3]. The technology has attracted the attention of other countries as well, including those in the Mediterranean basin [4,5] and the tropics [6-8]. VFCWs generally consist of a vegetated granular bed, a distribution device, and a drainage outlet as shown in Figure 1. The efficiency in treatment depends on a variety of design and operational parameters including the types of vegetation used, the type and configuration of substrates used, the feeding regime, and others.

![Figure 1. Typical configuration of a pilot-scale sludge-based VFCW](image)

VFCWs have been widely used to dewater and mineralize various kinds of sludge, including surplus sludge from activated sludge systems [4], agricultural slurries [9], and septage and faecal sludge [8]. During operations, the sludge is loaded in batches in an intermittent fashion. Contaminants in the sludge are then removed by an array of physical, chemical, and biological processes. Through physical filtration, a sludge deposit layer is formed, as the particulate contaminants are retained at the surface of the wetland bed. The sludge deposit layer then undergoes the dewatering and mineralization processes. In the VFCW system, the dewatering mechanisms mainly comprises of water drainage and evapotranspiration (ET) [10], whereas the sludge mineralization process occurs via microbial decomposition and disinfection [11].

In this paper, a review of the state-of-the-art of VFCWs treating sludge is presented, as well as the effects of varying design and operational parameters on treatment efficiency. The treatment performance of several pilot and full-scale sludge-based VFCWs are also summarized. Finally, future research directions and recommendations are discussed.

2. Parameters Affecting Treatment Efficiency

2.1. Solid Loading Rate (SLR) and Resting

The feeding regime of a sludge-based VFCW system usually includes a loading period, and a prolonged resting period. The loading of sludge into a VFCW system is measured in terms of solid loading rate (SLR). The term is expressed as the amount of dry solids loaded onto the bed per surface unit in a yr (or kg TS/m²/yr) [3]. It is a crucial operational parameter in VFCW operations. The value of SLR used for application is usually governed by climatic conditions and sludge quality. For example, Nielsen proposed an SLR of 60 kg TS/m²/yr with a feeding regime of 1/4 (dayloading/dayresting) for systems based in Denmark treating activated sludge [12]. However, a lower SLR of 50 kg TS/m²/yr was proposed for sludge containing high amounts of fats. It was also reported that SLR of 100 kg TS/m²/yr can be too high for systems located in Denmark. Reference [13] reported higher rates, ranging from 75 to 90 kg TS/m²/yr, for systems located in the Mediterranean basin, with a
feeding regime of 1/7 and 1/14 for lower and higher SLRs respectively. Even higher rates were reported for systems located in the tropic as reported by reference [14], whom suggested rates ranging from 100 – 350 kg TS/m²/yr with a feeding regime of 1/7.

According to Stefanakis and Tsihrintzis, it was found that systems receiving low, medium, and high SLRs (i.e. 30, 60, and 75 kg TS/m²/yr) have the same dewatering efficiencies, with sludge volume reduction of 96% and increase in TS content of up to 50% upon final resting [13]. This indicated that the systems, under the same climatic setting, can receive even higher rates than those applied in the study. However, a longer resting period would be required for higher SLR cases, in order to eliminate the remaining water content in the sludge deposit via ET. A similar finding was concluded by reference [14], who tested the effect of low, moderate, and high SLRs (i.e. 100, 250, and 350 kg TS/m²/yr) for systems in the tropics. The authors reported that dewatering efficiencies were generally the same for each SLR cases, with an increase in TS content from 1 – 6 % in the raw sludge, to 17 – 21 % in the final sludge, and a subsequent sludge volume reduction of 97 %. The drainage capacity of the system was a key aspect in the dewatering performance of the VFCW system [14]. Lower SLRs applied resulted in greater percentage of drained water as compared to higher SLR cases. In terms of system productivity, low SLRs resulted in better dewatering efficiencies as most of the water content was eliminated through water drainage, minimizing the need for ET and reducing the time required between subsequent loading periods (i.e. resting). Hence, the dewatering efficiency of VFCW significantly relies on the applied SLR and the resting period.

Sludge mineralization or stabilization is significantly affected by the intensity of the loading rates. According to reference [13], VS content in the sludge deposit decreased with SLR. As a result, sludge characteristics are further improved when lower SLRs are applied. Furthermore, the authors concluded that a final resting period can further improve the sludge’s dewatering and stabilization processes. This was also reported in reference [4] in which the authors reported that implementation of a final resting duration of 4 – 24 months further reduces the VS content.

2.2. Sludge Quality and Origin

The quality of the sludge and its origins plays an important role in treatment. Reference [15] reported that high concentrations of fats and oil in sludge can result in low dewatering efficiencies. This is because the high fats and oil content in sludge ultimately results in a lower density of sludge particles as well as a higher capillary water volume. In addition, reference [16] reported that higher VS content in sludge results in lower dewaterability of the sludge. This is because the organic particles have smaller contact angle as compared to inorganic particles, resulting in more water bound through capillary forces. Hence, the mineralization rate of organic matter directly affects the dewatering efficiency of the sludge.

On the other hand, reference [17] reported that the physical characteristics of sludge particles (i.e. particle size distribution) affects dewatering efficiency. This is because smaller particles fill up the pore spaces in the sludge, which increases the sludge specific resistance, and reduces the dewatering efficiency of the sludge deposit layer. Although the influent sludge characteristics are important elements to the treatment efficiencies of the VFCW system, its effect on treatment is still not fully understood yet [18].

2.3. Substrate Medium

The substrate medium configuration of a sludge-based VFCW system typically consist of a few layers of granular media of different sizes. In most cases, these layers are assembled in increasing sizes from the top to the bottom of the wetland bed as shown in Figure 1. They usually include a filter layer (top layer), a transition layer (middle layer), and a drainage layer (bottom layer). The total substrate height varies from 30- 80 cm [4,12-14,19,20]. To avoid hydraulic failure and clogging in the system, the top filter layer usually consist of sand [4,12,19] or fine gravel [13,14]. Although treatment efficiency is not significantly affected by the variation in substrate height, it was reported that media with higher porosity (e.g. when fine gravel is used instead of sand as a filter
layer) result in increased drainage capacity [13]. As a result, the drained water volume increased and ET rate decreases.

2.4. Wetland Vegetation
Wetland vegetation in VFCWs are essential elements in sludge treatment. They contribute significantly to the dewatering and mineralization of sludge. The most widely used species are common reeds (*Phragmites australis*) and cattails (*Typha latifolia*) [3]. According to reference [9], some of the desirable characteristics of vegetation in VFCWs include:
- Enhancing ET;
- Enhancing water drainage due to stem movement;
- Enhancing oxygen transport into the system; and
- Having root systems which acts as a site for microbial attachment.

The contribution of vegetation to sludge dewatering is mainly through ET, with estimated ET rates ranging from 4 – 12 mm/day [21]. According to reference [13], the presence of vegetation showed improvements in sludge volume reduction, with a subsequent increase of 2 – 6 % TS content in the final sludge as compared to systems that are unplanted. However, ET rates are extremely sensitive to seasonal variation, which will be further discussed in the following section.

In addition, wetland vegetation are capable of releasing oxygen in the rhizosphere, creating aerobic conditions in the sludge deposit layer which enhances the aerobic degradation process [1]. Wetland vegetation also indirectly contribute to sludge mineralization via stem movement which creates cracks on the surface the dry sludge, enhancing aeration at the upper layers of the sludge [1]. The cracks improve system drainage capacity by enhancing hydraulic performance and sludge porosity [12].

2.5. Climatic Conditions
As mentioned previously, dewatering of sludge is based on ET and water drainage. Climatic conditions strongly affect ET [21]. According to reference [21], an increase in ET rates of up to 30 % was observed for temperatures above 15 – 16°C. Additionally, reference [22] reported that sludge dewatering was increased by 40% during the summer period.

Depending on the resting durations, a relatively higher TS content was observed during the summer months compared to the winter months [3,22]. The higher temperature and ET values during the summer seasons enhances the dewatering efficiency of sludge, resulting in higher TS values measured.

3. Review and Discussion
For the past 20 years, numerous studies on the use of VFCW as an alternative to sludge treatment has been conducted [23]. Table 1 shows the treatment efficiencies of several VFCW systems around the world. The studies are presented in chronological order, for the purpose of identifying improvements in treatment efficiencies as research on this technology progressed.

| Sludge type | SLR (kg TS/m2/yr) | TS (%) | VS (%) | Volume reduction (%) | VS removed (%) | References |
|-------------|------------------|--------|--------|----------------------|----------------|------------|
|             | Initial Final    | Initial Final |          |                      |                |            |
| Activated sludge | 50; 60 | 0.5 | 40 | - | - | - | [3] |
| Septage and faecal sludge | 100; 200; 300 | 4 | 51 | 65 | 90 | - | [20] |
| Activated sludge | 20; 40 | 2.5 | 16 | 60 | 50 | 71 - 81 | 24 | [4] |

Table 1. Literature Survey of VFCW Dewatering and Mineralization Efficiencies
The reported data clearly shows the good overall effectiveness of VFCWs in sludge treatment. The system’s ability in dewatering sludge showed great potential with initial sludge volume reduction of 70 – 97%. This is also indicated by the increase in TS content from 1 – 6% in the raw sludge, to more than 50% in the final sludge deposit layer. The system is also capable of removing VS content in the sludge with an efficiency of 24 – 26%. The implementation of a final resting duration of 4 – 24 months could further stabilize the sludge, which further reduces the initial VS content to 40% [1,13]. The ability to stabilize sludge is crucial, because the final biosolids produced must comply with the USEPA criteria, which stated that at least 38% reduction of VS is necessary in order to reduce potential vector attraction [24,25]. In general, VFCWs are capable of providing adequate treatment efficiencies of sludge, which in most cases, are comparable to those of conventional treatment. These includes the use of centrifuges, belt filter presses, or vacuum filters (with final TS content ranging from 20 – 45%) [3] for sludge dewatering, and aerobic and anaerobic digestion systems (capable of removing 40 – 55% initial VS content in sludge) for the stabilization of sludge [26].

Based on the literature survey conducted, it was observed that further improvements on the dewatering efficiencies and SLR can be achieved, taking into account climatic conditions. The SLRs tested for systems in countries with warmer climates such as Malaysia [14] and Cameroon [20] are much higher compared to systems in countries with temperate [4,13] or colder climates [12]. This is because the high temperature and intensive ET rates allows for higher SLRs and shorter resting durations [3]. The high SLRs are also required to ensure sufficient irrigation for the survival of wetland plants. In addition, the higher SLR applications for systems under warmer climatic conditions allows for better treatment productivity.

Yet, it is interesting to note that these systems are able to effectively operate under colder climatic conditions [12]. Promising dewatering efficiencies with TS contents reaching up to 40% was observed for systems under cold climates. Proper control of the SLR intensity and feeding regime appears to be the key parameter to treatment effectiveness as well as ensuring smooth operations of the system (e.g. substrate clogging) [27].

To ensure that proper dewatering and mineralization rates are met, systems under colder climatic conditions should be applied with low SLRs accompanied by longer resting durations, while higher SLRs at shorter resting durations can be applied for systems under warmer climatic conditions. However, a standardized operation (i.e. SLR value and feeding regime), which takes into consideration the climatic conditions, has yet to be developed for these systems as indicated in Table 1. Hence, a standard operational strategy needs to be established. Often, optimization of operational strategies are based on a series of experimentations or experiences from older facilities. To-date, the safest way towards optimizing operational parameters is still based on conducting experiments under a specific climatic condition [3].

4. Future Directions and Recommendations
The current studies in this field have given useful insights into the effects of various operational and design parameters, as well as varying climatic conditions on treatment efficiencies. Nonetheless, a standard operational strategy has yet to be established, which is crucial in maintaining treatment efficiency and system lifespan. The effectiveness of treatment in VFCWs is accomplished by an array
of physical, chemical, biological, and microbiological processes, which occurs actively with regards to the system itself and its operation [27]. Modelling can be a useful way to attain more knowledge and determine the governing parameters that affect treatment performance, via simulating and describing the complex interactive processes that occur in the system. Hence, it is then possible to develop a more sustainable feeding regime and maintenance plan for the system. However, selection of an appropriate modelling approach is crucial to ensure the robustness and reliability of the simulated results.

According to [18], most published wetland models are either simple or black-box models. These includes the first-order kinetics models, and correlation models which correlates the pollutant concentrations in the influent and effluent. However, their applications are only limited to experimental conditions in which the model equations are derived from [28,29]. On the other hand, there are also more sophisticated models such as numerical or mathematical models reported in literature [30,31]. These models consist mostly of governing equations, each describing a particular process that occurs in the wetland system. They are more suited in modelling the VFCW system because they better predict treatment performances subjected to various operational, design, and external conditions [32]. In addition, experimental data are used to calibrate and validate the model. However, process-based mathematical models were developed for mostly subsurface flow constructed wetlands, with the majority of them developed specifically for municipal wastewater treatment [32].

To date, the only mathematical model for VFCWs treating sludge was developed by reference [33]. In this study, the authors developed the model, VF_Sep, using the commercialized MATLAB® software to simulate the effluent flux and corresponding nitrogen dynamics of several pilot-scale septage-based VFCW systems situated in Miri, Malaysia. The model was successful in describing the effluent flux as well as the corresponding ammonium (NH$_4^+$-N) and nitrate (NO$_3^-$-N) concentrations in the effluent when subjected to varying loading rates and sludge thicknesses. However, the scope of the study was limited only to effluent quality, with no considerations to sludge treatment. Hence, a VFCW sludge-based mathematical model which can simulate the sludge treatment mechanisms is still required.

5. Conclusion
Decades of research has shown that sludge treatment in VFCWs is a promising alternative to conventional treatment, which provides adequate treatment at low-cost, while being energy efficient, under various climatic conditions. A review of the effects of various design and operational parameters reveals that system efficiency is mostly governed by the SLR and feeding regime.

This study also highlights the lack of a standard operation strategy which is crucial in maintaining treatment efficiency and system lifespan. Further research on developing a sustainable operating regime is needed to ensure the reliability of the system in practice. Thus, modelling can be an approach to obtaining useful knowledge which can be used to ensure system efficiency and sustainability by determining the system performance, taking into account variations in influential parameters.

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