

Review

# Sludge Dewatering and Mineralization in Sludge Treatment Reed Beds

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**Abstract:** Sludge Treatment Reed Beds (STRBs) are widely used in Northern Europe to dewater and mineralize surplus sludge from activated sludge systems used to treat urban domestic sewage. STRBs are low-technology, energy-efficient, and do not require addition of chemicals. They dewater and stabilize the sludge and produce a final product that can be safely used as a fertilizer for agricultural crops. Long-term sludge reduction takes place in the reed beds due to dewatering and mineralization of the organic matter in the sludge. Although, in theory, a simple technique relying largely on natural processes, experience has shown that it is very important to understand and respect the basic design and operation requirements of STRBs. This paper describes the basic design and operation requirements of STRBs, with special focus on pivotal requirements to respect in order to secure proper functioning. Also, the paper summarizes performance experience concerning final dry matter content, degree of mineralization, emission of greenhouse gases, and degradation of micro-pollutants in STRBs. There are still a number of outstanding issues that are not fully understood, particularly in relation to the importance of the sludge quality for the dewatering in an STRB. Therefore, extreme care should be taken when attempting to extrapolate the use of STRBs to applications and regions outside of their ‘normal’ and documented area of application.

**Keywords:** biosolids; activated sludge; constructed wetland; treatment wetland; methane emission; *Phragmites australis*; sludge dewatering; sludge stabilization

## 1. Introduction

Wastewater treatment processes such as activated sludge treatment systems produce surplus sludge which has to be disposed of. The surplus sludge contains valuable nutrients and organic matter that can be used to improve soil quality and as a fertilizer for agricultural crops. However, the sludge needs long-term storage or biological, chemical, or thermal treatment to reduce its fermentability and the potential health risks from pathogens before the sludge can be applied in agriculture. The costs associated with the treatment and disposal of the surplus sludge is reported to be approximately one half of the costs of operating secondary sewage treatment plants in Europe [1]. Hence, there is a need for developing more cost-efficient sludge treatment solutions.

Sludge treatment processes generally have two main purposes: (i) thickening and dewatering whereby the sludge volume and hence the costs of subsequent handling, transportation, and disposal are reduced [2]; and (ii) stabilization of labile organic matter remaining in the sludge through microbial decomposition and disinfection [3]. Several successful and well-documented methods are available, but their capacity and operation vary, as well as the level of technological sophistication, infrastructure requirements, and the need for operational labor skills. Centrifuges and belt filter presses generally require the addition of conditioning chemicals (e.g., coagulants and/or polyelectrolyte) and a significant input of energy.

Compared to conventional sludge handling techniques, Sludge Treatment Reed Beds (STRBs) are low-technology, energy-efficient, and do not require addition of chemicals. STRBs dewater and stabilize the sludge and produce a final product that can be safely disposed of or used for agricultural purposes [4,5]. Using conventional technologies such as centrifuges and filter presses, the sludge typically reaches a dry matter content of around 20%, whereas the sludge in correctly designed and operated STRBs can reach a dry matter content of 20%–30% [2,6] and in optimal conditions up to 40% [7,8].

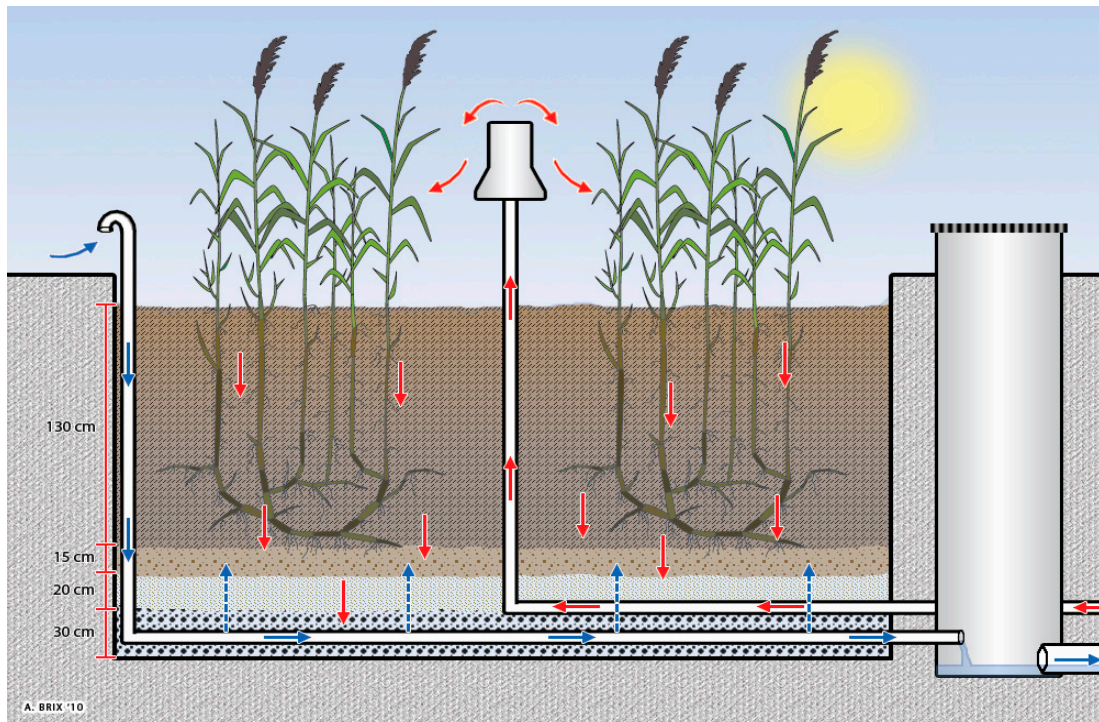
An additional advantage of STRBs as compared to most other technologies is that the water released from the sludge during dewatering is treated as it percolates through the bed. The typically high concentrations of Chemical Oxygen Demand (COD) in the reject water are reduced by more than 60%, and ammonium-N is usually nitrified. In addition, long-term sludge reduction takes place in the reed beds due to dewatering and mineralization of the organic matter in the sludge [9,10].

STRBs have been used in Europe for sludge dewatering and stabilization since the late 1980s. The largest experience comes from Denmark, where there are +100 full-scale systems in operation [11,12]. Experiences from these show that STRBs are capable of treating many types of sludge with a dry solid content between 0.5% and 5%, including sludge from water works [13,14]. Dimensioning and design of the STRBs depend on the sludge production (tons of dry solids/year), sludge type, sludge quality, and regional climate [7,11]. The operation of a system is divided into a number of phases related to different periods in the lifetime of the system. These phases comprise the periods of commissioning, full operation, emptying, and re-establishment of the system. Loading cycles are related to the sludge type and the maturity of the STRB. The sludge residue will, after approximately 10 years of operation, reach an approximate dry solids content of 25%–30% [14,15]. Experience has shown that the quality of the final product with respect to heavy metals, hazardous organic compounds, and pathogens after 10 years of treatment make it possible to recycle the sludge residue to agriculture [5,9,14,16–18].

## 2. Sludge Treatment Reed Beds

### 2.1. System Design

A sludge treatment reed bed system generally consists of a number of reed beds (usually more than eight) that are loaded in sequence by liquid surplus sludge from the wastewater treatment plant. The reed beds are built as planted vertical filters with an efficient drainage system in order to dewater the sludge effectively. The individual reed bed is usually established in a plastic lined excavation in the ground or with vertical concrete sidewalls on top of the soil, depending on site conditions (Figure 1). Walls should have enough freeboard (approx. 1.5 m) to stock up the sludge for a period of 10 years. In the bottom of the bed, a dense system of drainage pipes are placed in a layer of coarse gravel. The drainage pipes are vented to the atmosphere to secure air exchange in the pipes and hence an effective transfer of oxygen from the atmosphere to the drainage layer. On top of the drainage layer, one to three finer-textured layers of gravel, sand, or soil are placed to filter the water from the sludge. The upper so-called 'growth layer' is planted with the wetland grass Common Reed (*Phragmites australis*). The sludge is usually loaded onto the surface of the beds via vertical standpipes (Figure 2) with feeding lines buried in the drainage layer. Each bed requires emptying after a period of operation of about 10 years, after which the bed can be reloaded.



**Figure 1.** Diagram of a typical Sludge Treatment Reed Bed. The bed includes an impermeable basin to host the bed, plants, several layers of specific types of gravel, sand, and soil, a distribution system with vertical standpipes, and a drainage system with efficient air-exchange via ventilation pipes extending into the atmosphere (Drawing by Anton Brix).



**Figure 2.** Vertical standpipes through which the liquid sludge is distributed over the entire surface of the bed. The picture shows a situation where a planted reed bed, after emptying, are being loaded again, and plants are regenerating from the rhizomes remaining in the growth layer (Photo: H. Brix).

## 2.2. System Operation

Any system should have several (minimum eight) beds to alternate the loading and provide enough time between loadings for the biological and physical processes to take place during the resting periods (Figure 3). During operation, the sludge from the wastewater treatment plant (usually surplus activated sludge) is pumped through the vertical standpipes and distributed passively across the bed surface. The actual loading has to be relatively fast in order to secure a good distribution of the liquid sludge across the entire bed surface. The majority of the water percolates through the vertical filter and returns to the wastewater treatment system during the following hours/day. The solid fraction of the sludge stays on the surface of the bed. After each load, a dewatering period is allowed before a new layer of sludge is discharged on top of the dewatered sludge. The bed will then enter into a relatively long resting period where the sludge layer is allowed to dry. Oxygen diffusion via the drainage layer from below and through the cracked sludge surface into the sludge residue enables aerobic microorganisms to exist in the sludge residue. In a system with eight beds, the loading period initially will be a few days (3 to 7 days) followed by a long resting period of 21 to 49 days. As the system matures, the loading and resting periods may be longer, depending on actual hydraulic performance of the beds. The alternating loading and resting continues until the bed is filled-up with sludge and has to be emptied (after 8 to 12 years). The water drained from the sludge percolates through the sand and gravel. The prevailing oxic conditions in the non-saturated filter and the filtering effect of the media reduce the concentration of pollutants in the released water, which is sent back to the wastewater treatment plant for treatment.



**Figure 3.** Overview of a typical 40,000 person equivalent sludge treatment reed bed system in Helsingør, Denmark (56°00'41" N; 12°11'29.4 E, February 2015). The surplus sludge from the activated sludge treatment systems to the left is pumped to fourteen reed beds in sequence. The water draining from the reed beds (reject water) is returned to the activated sludge tanks. When the beds are filled up with sludge after 8 to 12 years, the dewatered and partly mineralized sludge are used as a fertilizer in agriculture. The Helsingør system was established in 1996 with ten beds. The system was expanded with four extra beds in 2013.

There are three periods in the operation of a planted reed bed system. During start-up (about two years), sludge loading should be less than the designed loading capacity (<50%). After start-up, the planted reeds are fully developed and the bed can be loaded with the designed loading capacity (In Denmark usually 50 or 60 kg dry matter per square meter per year). In the third period starting after about eight years of operation, some of the beds (maybe two out of eight) are emptied. Prior to emptying, the beds have a resting period during the (dry) summer months to maximize dry matter content of the sludge. After emptying, the beds can be loaded again, however, at a reduced rate initially

to secure good regrowth of the plants. The remaining beds are emptied successively, usually two beds in each of the following years for a system with eight beds. Hence, the emptying phase will usually be spread over four years to maintain continuous capacity even during the emptying phase.

### 2.3. Plant Functions

The Common Reeds in the reed beds have several important functions [19,20]. The root system and the stems help keep the filter open so that water can drain from the sludge to the drainage system. The growth of the rhizomes is important in this respect, as well as the wind-induced movements of the stems which results in cracks and openings in their periphery that allow the water to penetrate into the filter (Figure 4).



**Figure 4.** Openings in the sludge around the stems of *Phragmites australis* caused by the movements of the plants in the wind. These openings are important for maintaining a high water permeability in the sludge layer accumulated on the surface of the bed (photo: H. Brix).

Another important function of the plants is to remove capillary-bound water in the sludge by plant uptake and transpiration. The evapotranspiration rate of reeds is very high and can be even higher than the potential evaporation from an open water surface [21,22]. This is very important during the resting phase, where capillary-bound water in the sludge will be transpired, and as a result the sludge will tighten and crack. The cracks created are very important as these will allow easy transfer of air (and hence oxygen) into the sludge that will stimulate mineralization and further dewatering. The evapotranspiration is particularly important during the final resting period (usually several months during summer) before the beds have to be emptied. Because of the high evapotranspiration rates of the reeds, which exploit the capillary-bound water in the sludge, the dry matter content of the sludge may be as high as 40% when the beds are emptied (more commonly the final dry matter content is around 25%). The plants may have other functions, such as stimulation of microbial activities in the sludge [23], release of root exudates that interact with the sludge [24], and transfer of oxygen to the sludge through root release [25], but these functions are less documented and are probably of less importance. Oxygen diffusion from the roots into the sludge residue might enable aerobic microorganisms to exist close to the roots and in the sludge residue.

### 3. Design and Operation Considerations

As always when a new technology is introduced into the market, some operational problems are likely to be observed in the first full-scale systems. Furthermore, some engineering design offices are likely to adopt and sell the system without proper knowledge of the critical design and operation issues. This has been the case in Denmark, and has led to the situation that several systems have had serious problems. The common problems observed include poor growth of reeds after one or two years, and no reeds at all in the worst cases, and liquid anaerobic sludge with a high water content in the beds (Figure 5). This situation is associated with inefficient drainage of the water from the bed. The dry matter content of the sludge will be only 10%–12%, even after a resting period of several months. In the following sections, the main reasons for such problems are described.



**Figure 5.** Typical sludge treatment reed beds with operational problems as indicated by the reduced and clumped growth of the reeds (photo: H. Brix).

#### 3.1. Design and Construction Issues

##### 3.1.1. Too Few Beds

A number of systems have been designed with only two to six beds. This has been found to be problematic as the resting periods of the individual beds are relatively short. The problem is compounded during the period of sludge emptying, where the beds that are going to be emptied are taken out of operation for an extended period. Under Danish climatic conditions, the number of beds should allow for a minimum resting period of 30 days (preferably longer) during the emptying phase where some beds have to be taken out of operation for an extended period.

##### 3.1.2. Damaged Drainage System

The drainage pipes are likely to be damaged if, during the construction phase, heavy machinery is used within the beds. This may result in the breakage and/or compression of the drainage pipes with resulting inefficient drainage. Also, the levelling or inclination of the drainage system is important. The drainage system must be laid down with a slight slope (1% to 2%) to secure efficient runoff of drainage water. If levelling is not correct and some parts of the drainage pipes are continuously filled with water (e.g., at low spots), there will be no possibility for air ventilation of the drainage pipes,

and the oxygen transfer to the drainage layer will be hindered. Systems have also been designed and constructed with standing water in the drainage layer, which evidently has the same negative effect.

### 3.1.3. Wrong Composition of the Growth Layer

The upper layer of the filter material, the growth layer, is meant to support the growth of the plants, but at the same time the layer must have a composition (texture) so that water can easily drain through the layer. The contents of clay and fine silt-particles must, therefore, be low, and the content of organic matter must be restricted. The texture of the material should be characterized by a high degree of uniformity (a steep grain-size distribution curve) to secure high water permeability. If the composition of the growth layer is wrong (and perhaps the layer was compacted from the use of heavy machinery), the water from the sludge will not be able to drain from the bed at a sufficiently high speed. The bed will remain wet and the sludge will not be dewatered sufficiently.

### 3.1.4. Wrong Planting Technique

Planting of the systems is best done by potted seedlings at a density of approximately four pots per m<sup>2</sup> into the growth layer. After planting, sludge loading rate and frequency have to be fitted to the need of the plants for watering and fertilization. This means a reduced capacity of the system for the first two growing seasons. Some suppliers have used 20 cm by 20 cm 'blocks' of root systems from natural reed stands instead of potted seedlings and have placed these blocks on top of, and not buried into, the growth layer. By using this planting technique, the suppliers argue that the beds can be loaded at full capacity from the beginning, without damaging the plants. The experience shows, however, that although the reeds from the blocks will survive and look healthy in the beginning, the roots and rhizomes will not grow into the growth layer and the sludge surrounding the root-blocks to any significant extent. Hence, after a couple of years, these systems generally have serious operational problems.

## 3.2. Operation Issues

### 3.2.1. Wrong Running-In Period

During running in, the main emphasis of the operation is to secure an efficient establishment of the reeds. During the first year of operation, sludge loading rate and frequency should be carried out with the main purpose of watering and fertilizing the reeds. Even in the second year, the loading has to be reduced as compared with full capacity loading, to stimulate plant growth and establishment. If the sludge loading rate is too high during the running-in period, and if the loading frequency does not secure sufficient water for the reeds, the plants will not establish well and will eventually disappear from the system once the sludge layer increases in thickness.

### 3.2.2. Overloading

The treatment capacity of an STRB, usually given as kg of dry matter per square meter per year, is an important design parameter. The treatment capacity depends on several factors including climate and sludge type and quality. For economic reasons, systems are usually designed to receive as much sludge as possible, without jeopardizing performance. If the systems are overloaded compared to their treatment capacity, this is likely to result in operational problems, with negative effects on the plants and hence the sludge dewatering and mineralization.

### 3.2.3. Lack of Resting Phases

Some systems have been operated continuously with daily loadings on all beds and no resting periods. Even though water will drain from the beds, the sludge will not dry out, and after a period, serious problems with insufficient water drainage will occur. A resting phase that is long enough for the sludge to dry out and crack at the surface is important for sustained operation. The relative length

of the loading and resting phases is one of the most important operational parameters. During the initial years, the loading phase may be relatively short, maybe just a couple of days, followed by a two to six week resting period. Once the beds become older and the layer of accumulated sludge in the beds becomes thicker, the loading period may be longer (maybe one week or longer) followed by an equivalent longer resting period (seven weeks or longer). The maximum drainage velocity during loading is a good indicator that should be used to decide on the duration of the loading period.

### 3.3. Sludge Quality

The majority of STRBs in Denmark are designed to process sludge from urban domestic wastewater treatment systems using activated sludge as the treatment process. As treatment demands in Denmark include efficient removal of both nitrogen and phosphorus, these systems usually operate with relatively long sludge detention times and a high sludge age to secure efficient nitrification and denitrification. Phosphorus is usually removed by biological P-removal supplemented with chemical precipitation by iron and/or aluminum salts. Because of the long detention times of the sludge in the activated sludge systems, the sludge delivered to the STRBs are usually 'stabilized' and have a low oxygen demand.

The sludge quality varies significantly between systems as well as over time in the individual systems. The sludge quality is, however, very important for the ability of STRBs to dewater and mineralize the sludge. In general, good results have been obtained for 'normal' stabilized activated sludge from urban domestic wastewater treatment systems, and systems have performed well at a loading rate of 60 kg dry matter per square meter per year. However, some systems have experienced problems that can be associated with sludge quality. The knowledge about sludge quality parameters and how these affect capacity and performance of STRBs is, however, still insufficient.

Effective biomass–water separation is essential to the activated sludge process in biological wastewater treatment. Bioflocculation transforms bacterial cells into sludge flocs, which facilitates biosolids–water separation including sludge sedimentation, compression, and dewatering. Extracellular polymeric substances (EPS, biopolymers that surround the bacterial cells) are believed to play an important role in the formation of sludge flocs [26]. However, the exact effects of EPS on bioflocculation and sludge–water separation are still unclear [27,28]. The EPS abundance of the sludge can be sensitive to the environmental variations, such as changes in organic loading rate, detention time, and carbon and nitrogen sources. It is likely, that any factor in the wastewater treatment plant that will influence the amount of EPS is also likely to influence the dewatering in the STRBs.

The following parameters have all been shown, or suggested, to be associated with operational problems in STRBs:

- Mixing of sludge from an anaerobic digester with activated sludge prior to dewatering in the STRBs. This may result in a mixed sludge with a high oxygen demand that has difficult dewatering properties.
- The physical influence of using certain types of high-pressure pumps for transferring the activated sludge to the STRBs may disrupt floc structure and negatively impact dewatering.
- Transport of sludge in kilometer-long pipes with resulting long transport time, and/or storage of sludge prior to spreading on the surface of the reed beds has been shown to negatively affect sludge dewatering in the reed beds.
- Sludge from municipal wastewater treatment systems treating a significant fraction of industrial (including agro-industrial) wastewater has been shown to be difficult to dewater. Some studies indicate that the contents of fat in the sludge may be correlated with the dewatering difficulties [29].
- Addition of precipitation chemicals for phosphorus removal may influence dewatering properties.

Because of the coherence between sludge quality and dewatering properties, it is very important in any project, prior to dimensioning, to assess the sludge quality, including its degree of stabilization,



e.g., its oxygen demand, its bio-flocculation properties, and its dewatering characteristics. It has been suggested to use simple laboratory measurements such as 'Specific Resistance to Filtration' and 'Capillary Suction Times' as means to assess dewatering properties of the sludge, but the relation to sludge dewatering in STRBs has not as yet been established [27,28,30].

#### 4. Environmental Issues

##### 4.1. Greenhouse Gas Emission

Emissions of CO<sub>2</sub> (carbon dioxide) and CH<sub>4</sub> (methane) from STRBs are inevitable, since one of the main purposes of such systems is to stimulate microbial mineralization of various organic compounds. Carbon dioxide emitted from wastewater treatment processes is considered to be originally fixed from the atmosphere and, therefore, climate neutral. Therefore, the CO<sub>2</sub> emitted from STRBs should not be considered a problem in relation to the greenhouse effect. It has been shown that STRBs emit 2 to 9 times less CO<sub>2</sub> equivalents than conventional treatment methods [5,17,31] and that greenhouse gas emissions make an insignificant contribution to the total carbon footprint of STRBs compared to raw materials and energy consumption [17]. Thus, STRBs seems to be a good alternative for sludge treatment in terms of climatic impact. It is relevant, however, to make sure that greenhouse gas emissions from an STRB are not higher than necessary, and that the contribution from CH<sub>4</sub> is kept to a minimum.

Olsson et al. [32] reported that the climatic impact from CH<sub>4</sub> emitted from an STRB was low, despite the approximately 25 times higher Global Warming Potential (GWP) of CH<sub>4</sub> compared to that of CO<sub>2</sub> on a 100-year time scale. Moreover, the presence of reeds partly counteracts the emissions due to photosynthetic carbon uptake from the atmosphere, which in a reed wetland in Vejlerne Nature Reserve, Denmark, has been found to comprise 43,000 kg·CO<sub>2</sub>·ha<sup>-1</sup>·year<sup>-1</sup> [33]. Hence, the reeds in the STRB have the potential to significantly mitigate the CO<sub>2</sub> emissions from the beds. Compared to an STRB in Spain [31] which emitted 255 CO<sub>2</sub> equivalents (103 kg·ha<sup>-1</sup>·year<sup>-1</sup>) as CH<sub>4</sub>, the Danish well-functioning STRB emitted 220 times less CH<sub>4</sub>. This may be related to more anaerobic conditions in the Spanish systems, different sludge composition, as well as the warmer climate in Spain compared to Denmark. The differences may partly be an effect of season as the Danish study was conducted in the late autumn when microbial processes are slow due to the low temperature.

##### 4.2. Pathogens

The contents of pathogenic bacteria must be reduced before sludge can be spread on agricultural land as a fertilizer. Studies on the storage of wastewater sludge as a possible low-cost means of pathogen reduction prior to its beneficial reuse have shown that even after a 12 month storage period, levels of Salmonella, fecal coliforms and streptococci, and Giardia cysts were too high to be considered an adequate treatment option [34]. Studies in STRBs have shown that the number of pathogenic bacteria (Salmonella, enterococci, and *Escherichia coli*) in the sludge residue during a period of 3–4 months after the last loading was reduced to <2/100 g (Salmonella), <10 Colony-forming Units/g (enterococci) and <200 number/100 g (*E. coli*). For enterococci and *E. coli* the reduction was approximately log 5 and log 6–7, respectively [8]. Thus, from a hygienic perspective, it is safe to recycle the biosolids to agriculture [5,35].

##### 4.3. Organic Micro-Pollutants

Wastewater and the sludge produced from the wastewater treatment process contain a vast amount of organic micro-pollutants, some of which are very undesirable in the environment. Hazardous organic compounds such as linear alkylbenzene sulfonates (LASs) and nonylphenoethoxylates (NPEs) have been reported to be degraded in an STRB with a mineralization of 98% of LAS and 93% of NPE [36]. Also, the concentrations of personal care products (fragrances) and various pharmaceuticals have been reported to be reduced effectively [6]. In general, the content of hazardous organic

compounds in the sludge residue is reduced to such a degree that the sludge conforms to the limits and norms for deposition on agricultural land [8,14].

#### 4.4. Heavy Metals

Heavy metals contained in the fresh sludge from a wastewater treatment system will remain in the sludge residue, and the concentration is likely to increase over time because part of the organic contents of the sludge (typically 20%–30%) are mineralized over time. If the biosolids have to be spread on agricultural land, the concentrations of heavy metals in the sludge have to remain below some legal limit values for the application to farmland [14]. It is, therefore, important that the heavy metal content of the fresh sludge, and hence the wastewater in the wastewater treatment plant, is already low in heavy metals. For Danish systems, the quality of the sludge residue has in general, and even for sludge residues older than 20 years, been reported to comply with the Danish regulations when based on the contents of heavy metals in relation to phosphorus [6,12,14,37,38].

### 5. Discussion

Processing of surplus sludge from wastewater treatment systems can be efficiently carried out in STRBs. This approach has several advantages compared to conventionally used handling techniques. In addition to dewatering, the organic matter in the sludge is partly mineralized, thereby minimizing the sludge volume and improving the sludge quality [14]. The overall sludge volume reduction occurs without the use of chemicals and involves only a very low level of energy consumption for pumping sludge and reject water. The final sludge product can safely be applied as a fertilizer on agricultural lands. The capital costs of STRBs are usually higher than mechanical dewatering devices. However, the operational expenses are significantly lower than those of mechanical dewatering, delivering an economic break-even of about 3–5 years [12].

Although STRBs in theory are relatively simple systems that rely largely on natural processes, experience has shown that it is very important to understand and respect the basic design and operation requirements. Experience from Denmark has proven that if some of these requirements are not respected, the systems are likely to fail. There are, however, still a number of outstanding issues that are not fully understood, particularly in relation to the effects of sludge quality. There are no accepted means to evaluate the ease with which sludge will release its water, and even less so for evaluating how sludge can be expected to dewater in a planted reed bed. Therefore, extreme care should be taken when attempting to extrapolate the use of STRBs to applications and regions outside of its 'normal' and documented area of application. Having said this, there is no doubt that STRBs have a great application potential in other climatic regions and for several types of sludge. Applications in subtropical and tropical areas are still on an experimental scale. However, STRBs are likely to perform more efficiently in warm and dry climates due to the more benign and stable temperatures, which should accelerate the rate of the biological processes.

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