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Review

Sustainable Dewatering of Industrial Sludges in Sludge Treatment Reed Beds: Experiences from Pilot and Full-Scale Studies under Different Climates

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Featured Application: This review paper is the first one that summarizes the limited available information on the application of the green technology of Sludge Treatment Reed Beds (STRBs) for dewatering of industrial sludge. Although STRBs are widely used as a low-cost and sustainable nature-based solution for domestic sludge dewatering, the number of applications for industrial sludge treatment is very limited. This study presents the few available pilot and full-scale STRB systems from various countries that receive and treat sludge from industrial wastewater treatment plants or sludge from Water Works. The overall efficiency and performance for this particular application is also discussed along with the advantages of this green technology. Finally, this study proposes the optimum design parameters for proper dimensioning and operation of STRBs for industrial sludge dewatering.

Abstract: Sludge treatment reed beds (STRBs) are an established sludge treatment technology with multiple environmental and economic advantages in dewatering sludge generated during domestic wastewater treatment. However, little is reported regarding their appropriateness and efficiency for the treatment of sludge produced during industrial wastewater treatment and from water works. These sludge types may have significantly different quality characteristics than typical domestic sludge and may contain constituents that could affect their dewaterability. Therefore, the dewatering of these industrial sludge types is usually tested in small-scale pilot STRBs before the construction of full-scale systems. This paper presents and summarizes the state-of-the-art experience from existing pilot and full-scale STRB systems from various countries and climates treating sludge from various industrial sources, evaluates the suitability and the advantages of this sustainable treatment technology, and proposes the required dimensioning for efficient full-scale STRB operation and performance.

Keywords: ferric sludge; water works; sludge treatment reed bed; sludge treatment wetland; sludge dewatering; hazardous organic compounds; heavy metals; reuse; stability; nature-based solutions

1. Introduction

Wastewater treatment processes typically result in the production of a by-product material, known as sewage sludge. Sewage sludge is produced at various points along the treatment train of wastewater treatment plants (WWTPs), namely in the primary sedimentation stage, the biological stage (e.g., aeration tanks), and the secondary sedimentation stage. Hence, depending on the treatment stage, sludge can be characterized as primary, secondary, biological, mixed (a mixture of primary and secondary sludge) or tertiary (from tertiary or advanced treatment stages) [1]. As any wastewater source, sludge can be originated from households, commercial and municipal areas, industrial facilities, agro-industries, surface runoff and stormwater. Sludge production is continuously increasing following a respective increase in the population numbers connected to centralized WWTPs and the adoption of stricter environmental legislation [2]. Typical sludge production in activated sludge plants, i.e., the most widely applied wastewater treatment method, is up to 2.5 kg per individual per day [1]. This means that, for example, for a population of 100,000 inhabitants, the generated sludge would reach 250 t/day. Municipal sludge was produced in the European Union (EU) at an annual rate of 8 million tons in 2016 [3,4], a figure that is estimated to further increase and reach 13 million tons of dry solids (ds) this year [5].

Although the sludge volume represents a very small fraction (typically less than 1%) of the total wastewater volume that is treated at a WWTP, the overall cost for sludge management and handling could account for up to 50% of the total operation costs of the WWTP [1]. In addition, considering the circular approach based on which all waste should be viewed as a valuable resource rather than as waste [5], sustainable sludge management options are now required. Moreover, the target of eliminating landfilling or energy-consuming incineration means that alternative eco-friendly solutions are in focus [5].

Various technologies have been applied for sludge dewatering, such as mechanical treatment (i.e., decanters, centrifuges, and screw-presses) and simple sand drying beds in warmer climates, as have environmentally friendly solutions, such as sludge treatment reed beds (STRBs), also known as sludge treatment wetlands [1]. Sludge treatment in reed beds/constructed wetlands was developed in the late 1980s and today represents a cost-effective and easy-to-run nature-based solution for the dewatering and stabilization of sludge that can be applied at small and also at large scales [6–8]. Comparing STRBs with mechanical dewatering systems and sludge disposal, STRB technology typically has slightly higher investment costs but significantly lower operation costs. A life cycle cost analysis and comparison of STRB and mechanical systems for the dewatering of activated sludge of 550 t ds/year revealed that the STRB system is a cost-effective alternative [9,10]. As an eco-friendly wetland technology, STRBs do not require the use of polymer coagulants for the dewatering process, and due to the small amount of energy input needed, the absence of complex electro-mechanical equipment, and the use of natural materials and processes, STRBs as all treatment wetland systems are viewed as a green treatment technology with a minimal carbon footprint [1,10–13].

STRB technology is widely applied mostly for municipal sludge dewatering in Europe. For example, this technology has been used in Denmark for almost 30 years. Sewage sludge contains organic matter and nutrients; hence, it is widely used as a soil amendment, as a fertilizer in agriculture, and in other environmental applications (e.g., forestry and land reclamation) [8,14,15]. However, sewage sludge may also contain contaminants such as micropollutants, emerging contaminants, and trace elements (e.g., heavy metals and pathogenic microorganisms) that may have an adverse environmental impact [14,16,17]. There is limited study of the fate of various micropollutants and emerging contaminants in STRBs. STRBs have been found to be capable of removing some pharmaceuticals from domestic sludge (e.g., diclofenac [18] and antibiotics, i.e., ciprofloxacin and azithromycin [19]) and antibiotic-resistant genes [20,21], but generally, there is not sufficient information yet regarding the behaviour and performance of STRBs in the removal of such micropollutants in STRBs treating domestic and/or industrial sludge. STRBs are also much more efficient in the degradation of hazardous organic compounds, such as linear alkylbenzene sulfonate (LAS), nonylphenol polyethoxylates (NPE), di-(2-ethylhexyl)phthalate (DEHP), and certain polycyclic aromatic hydrocarbons (PAHs) than conventional methods [9,11,12]. These are important aspects for sludge reuse; for example, the Danish Environmental Protection Agency (DEPA) and the EU have regulated the contents of nutrients, heavy metals, and hazardous organic compounds in sludge spread on agricultural land (Table 1; [9,11]).

Table 1. Regulatory limits in Denmark and the European Union (EU) for heavy metal and hazardous organic compound contents in sludge reused in agriculture [22,23].

Parameter	EU		Denmark	
	Directive 86/278/EC [22]	EC Working Document on Sludge, 3rd Draft [23]	BEK No. 1001 of 27/06/2018	
Metals	**mg/kg ds**	**mg/kg ds**	**mg/kg ds**	**mg/kg TP** [1]
Cadmium (Cd)	20–40	10	0.8	100
Copper (Cu)	1000–1750	1000	1000	-
Nickel (Ni)	300–400	300	30	2500
Lead (Pb)	750–1500	750	120	10,000
Zinc (Zn)	2500–4000	2500	4000	-
Mercury (Hg)	16–25	10	0.8	200
Chromium (Cr)	-	1000	100	-
Organic compounds CONTAMINANTS	**mg/kg ds**	**mg/kg ds**	**mg/kg ds**	**mg/kg TP**
LAS	-	2600	1300	-
PAH	-	6	3	-
NPE	-	50	10	-
DEHP	-	100	50	-

EC = European Council; ds = dry solids; LAS = linear alkylbenzene sulfonate; PAH = polycyclic aromatic hydrocarbons; NPE = nonylphenol polyethoxylates; DEHP = di-(2-ethylhexyl)phthalate; BEK = Bekendtgørelse; TP = Total phosphorous.

Generally, experience has shown that STRBs can treat most types of sludge with ds contents between 0.1 and 5% [1]. Some sludge types, especially those of industrial, i.e., non-domestic, sources may, in general, be difficult to dewater and even unsuitable for an STRB system, e.g., sludge rich in oil and fat. Industrial sludge is considered a more difficult application and technically more challenging for effective dewatering, since it may contain heavy metals, nutrients, hazardous organic compounds, oil, and fats at much higher levels than typical sludge of domestic origin; thus, its treatment, dewatering, and/or disposal can be problematic considering the legal requirements. This is why the vast majority of STRB facilities worldwide are designed for the dewatering of domestic sludge.

On the other hand, there is an intensively increasing worldwide interest in the application of constructed wetlands (or reed beds) technology for industrial wastewater treatment [24], which also encompasses the reed bed system for sludge dewatering. Thus, over the last few years, there has also been a respective increase in research and development interest in the application of this green technology for industrial sludge dewatering. This gradual shift of research interest to industrial waste comes as a result of the proven high treatment efficiency of this natural treatment technology and the realization of the actual treatment capacity it possesses [13,24], as well as of the better understanding of its multiple environmental, technical, and economic benefits and the desire for sustainable options in the global water/wastewater industry.

However, as this tendency is relatively new, most of the available studies and reports in the international literature on STRBs deal with sludge from domestic WWTPs. The published literature on the feasibility and efficiency of industrial sludge treatment in STRB is very limited, and only very few case studies (mostly pilot projects) have been presented at international conferences or reported in journal articles and/or book chapters. This means that there is gap in the respective literature not only due to the small number of studies but also due to the fact that this information is scattered and not easily accessible.

Therefore, the main goal of this study is to cover this literature gap and summarize the current status and state-of-the-art knowledge and experiences regarding the design, operation, and efficiency of STRBs for industrial sludge dewatering. For this, the available published literature is reviewed and summarized while new case studies are presented in the first single and comprehensive overview paper on this specific application of STRB technology. Thus, this paper presents an overview of STRB design and operation and briefly describes the concepts and the performance of the few existing

STRB case studies (both pilot and full-scale projects) treating various sources of industrial sludge from different countries and climates, outlining the advantages and challenges of these systems as they arise from practical experiences.

2. Sludge Treatment Reed Bed System and Industrial Sludge

2.1. Description

STRBs are an established nature-based technology for sludge treatment. The concept of an STRB is similar to that of a vertical flow constructed wetland [1,25]. Most of these systems are found in Europe and the USA, e.g., in France, Denmark, Germany, Poland, and Sweden [26–29]. Almost 20% of the produced sludge in Denmark is treated in STRB systems [8,11], mostly in villages and small cities with populations of up to 10,000 inhabitants, though there are large-scale systems (serving over 100,000 inhabitants) as well. Lately, this sustainable technology has been introduced into various Mediterranean countries, such as in Greece, Italy, and Spain [30–34], as well as in China [35] and the Middle East [36], due to the favorable, i.e., warmer, climates.

An STRB is a concrete or trapezoidal earthen basin [32,37], the bottom of which is typically covered by a low-permeability sealing material, such as a high-density polyethylene (HDPE) geomembrane, to prevent leaching to the underground formations and the groundwater. The basin is filled with gravel and sand of different sizes and thicknesses [1], while on top of the substrate layer, local wetland plant species are planted, such as common reeds or cattails (*Phragmites australis* or *Typha latifolia*). A sludge distribution pipe network spreads the feed sludge across the surface of the bed, where sludge is dewatered through passive vertical drainage and evapotranspiration (Figure 1) [16,37,38]. A drainage pipe network is placed into a cobble (i.e., large stone) layer above the geomembrane and collects the drained water. The drainage network is connected to pipes that facilitate the passive aeration of the bed, which has been found to be beneficial for the dewatering performance of the system [1,37–39].

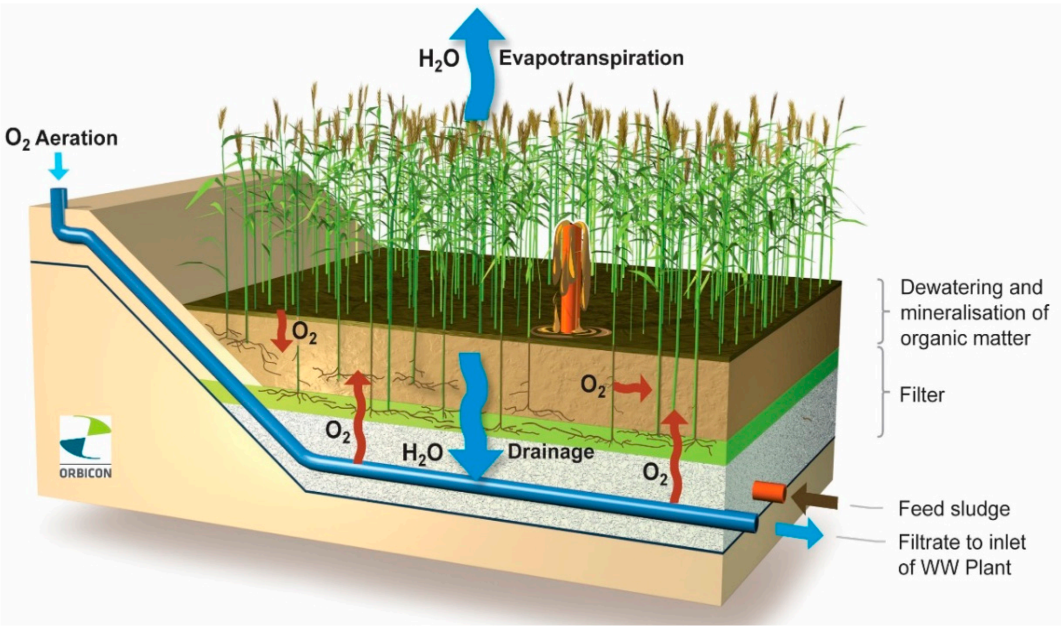

Figure 1. Schematic cross-section of a sludge treatment reed bed (STRB) system indicating the sludge layer, the porous media layer, the feeding pipes, and the drainage network (courtesy of Orbicon).

Vegetation and passive ventilation create favourable conditions for the conversion of degradable organic matter to a more stable humic form [33,40]. The dewatering process along with organic matter mineralization results in the reduction of the sludge volume, and the accumulated residual sludge is continuously incorporated into the filter media layer where the plants are established. As time passes, the depth of the mineralized residual sludge layer increases at an approximate accumulation rate of 10–15 cm/year, which depends on the quality of the feed sludge [1]. Typically, after 8 to 12 (even up to 20) years of continuous operation, the layer of the dewatered and also mineralized residual sludge is removed from the basins and then recycled as a fertilizer or as a soil conditioner [8,16,37,41,42]. There is a wide range of sludge types that can be dewatered in STRBs such as activated sludge, digested (anaerobic) sludge, and sludge from waterworks (WW). Experience has shown that STRBs can treat sludge of varying qualities, possessing a comparable or even higher dewatering capacity than conventional dewatering methods.

The effective dewatering and operation of an STRB depends on the quality of the feed sludge, the climatic characteristics, and proper design and construction [1]. The sludge loading rate (SLR; kg ds/m^2/year) represents a key parameter in STRB design, and mostly depends on the sludge quality and the climate [1,37]. Usually, a first pilot testing phase is recommended before the implementation of a full-scale STRB to determine the dewatering ability and efficiency, especially when an industrial sludge is to be treated. A typical pilot study would consist of 3–12 beds, each with an area of up to 2 m^2 (or more). A typical testing period lasts 4–12 months, although there are pilot experiments operated for up to 3 years. Such a trial usually aims at identifying the suitability of the feed sludge for treatment in an STRB, the required number of beds, the optimum SLR and length of the feeding and resting periods, the dewatering efficiency (L/s/m^2), the drained water quality, the residual sludge quality, and the plant growth. A pilot study will also provide the necessary guidance for potential modifications at the WWTP facility in order to decrease the content of any undesired materials in the raw sludge (e.g., heavy metals, fats and oil, etc.). However, there is not a unanimously and widely accepted STRB design, even for similar sludge types [1]. The number of beds in an STRB system varies between 1 and 24, the bed area between less than 100 and more than 3000 m^2, and the SLR between 30 and more than 100 kg ds/m^2/year [1,9].

2.2. Operation

STRB operation is based on feeding cycles, where each cycle consists of loading and resting periods [1,11]. The loading period usually lasts a few days or even few weeks and is followed by a resting period without sludge applications to allow for sludge dewatering through drainage and evapotranspiration [1,11]. For example, the design developed by Orbicon for the Danish climatic conditions suggests a cycle of 1–2 weeks of loading and then 5–10 weeks of resting, i.e., without loads of new sludge [38,41], while for the temperate climate of Greece, the respective figures are 1 week of loading and 1–3 weeks of resting (varying between seasons) [1,30,31]. In general, the duration of the feeding and resting periods is decided according to the sludge quality, the climatic conditions (i.e., cold climates require prolonged resting periods), the seasonal variations, the age of the STRB, the ds levels in the feed sludge, and the depth of the residual sludge layer [9,11,37].

Although the operation of STRBs is relatively simple, their effective dewatering performance depends on the proper management of the feeding cycles to prevent overloading the beds. A properly managed STRB can reach 40% ds under colder climates (e.g., in Denmark) [38,41] or even higher in warmer climates (such as 60% in Greece [30,31]), figures that are higher compared to those for the energy-intensive mechanical dewatering methods. Due to the limited energy input required for the operation of STRBs, these systems are also much more energy efficient [43–45] and act as a carbon sink due to carbon fixation by the reed plants [1,46–48].

2.3. Industrial Sludge in STRB

The term "industrial sludge" is generally not clearly defined; however, it should be understood that it refers to sludge produced at the WWTPs of single industries and public WWTPs receiving not only municipal effluents but also effluents from industrial facilities, and sludge produced at the WWTPs of agro-industrial facilities, e.g., the food industry, aquaculture, dairy farms, olive mills, abattoirs, as well as sludge produced at water works (WW) [49]. The sludge produced in these facilities may include pollutants that are not present at all in the sludge derived from domestic wastewater, such as heavy metals, oil and fat, and hazardous organic compounds, or that are present at much higher concentrations, e.g., higher nutrient content (e.g., nitrate and phosphate) and higher oil and fat content. Hence, these sludge types are more difficult to manage due to their reduced dewaterability and the potential contamination of the residual sludge. In particular, sludge from WW, i.e., the purification facilities that produce potable water, is typically rich in iron and/or aluminium but has a low organic and oil and fat content. Sludge produced by the food industry, e.g., slaughterhouses, dairy farms, aquaculture farms, etc., has higher contents of organics (i.e., oil, fat, proteins, and carbohydrates), heavy metals, nutrients, and suspended solids. This means that these types of sludge represent an environmental hazard.

2.3.1. Organic Matter

Insufficient sludge dewatering is often related to the feed sludge quality. The ratio between organic and inorganic matter is a commonly used parameter for assessing the sludge dewatering properties. The content of organic matter is usually expressed by determining the "loss on ignition" (LOI). The water retention capacity of sludge that has a high LOI, i.e., a high organic matter fraction, is much higher than that for a sludge with low LOI, i.e., sludge with a higher inorganic fraction, since the organic matter content highly affects the free water content. Thus, the higher the organic matter content, the lower the free water content and the higher the capillary water content [46], making dewatering more difficult [25]. The comparison of the organic matter content (expressed as LOI) in the feed sludge with the ds content in the residual sludge in a large number of STRBs revealed that higher organic matter content in the feed sludge results in lower ds content in the residual sludge (Figure 2).

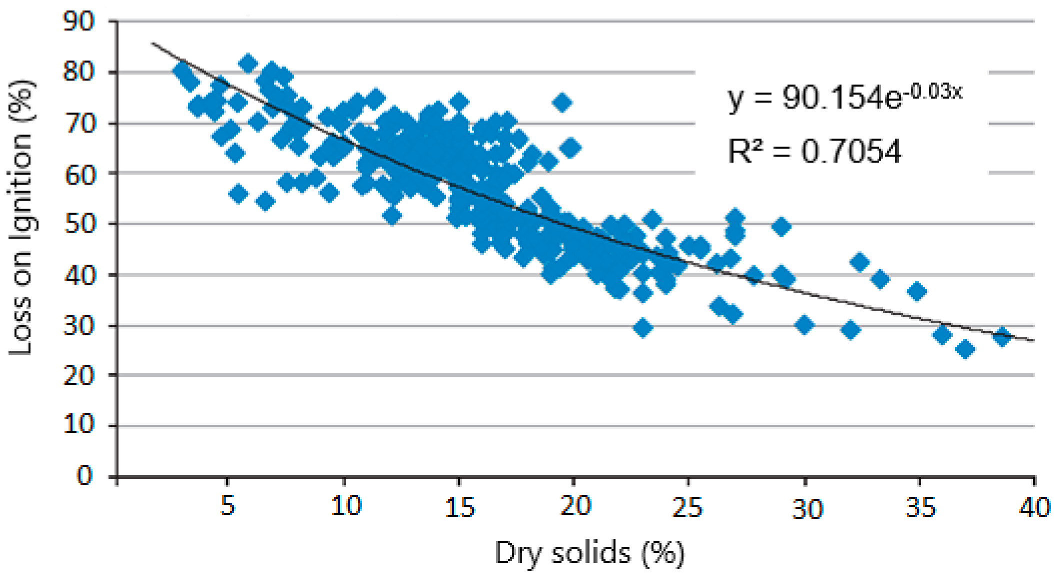

Figure 2. Organic matter content (loss on ignition—LOI) in the feed sludge and dry solids content in the residual sludge—correlation in STRBs. Practical experiences indicate that a LOI higher than 65% significantly limits sludge dewatering.

2.3.2. Oil and Fats

One visual way to evaluate the dewatering process in STRBs is the observation of cracks in the upper sludge layer during the resting period. Sludge with a high oil and fat content does not easily form cracks and openings during the resting period, which limits the natural aeration from the atmosphere on the bed surface. If such cracking is not observed, this probably implies insufficient sludge dewatering [25]. Therefore, a feed sludge with high fat and oil content should be considered during the design phase in order to avoid a negative impact on the ds content in the residual sludge

(Figure 3). Experience has shown that a feed sludge with a fat content higher than 5000 mg/kg ds significantly affects the dewatering process and contributes to the creation of an anaerobic environment in the residual sludge layer, indicated by a black colour and unpleasant odour.

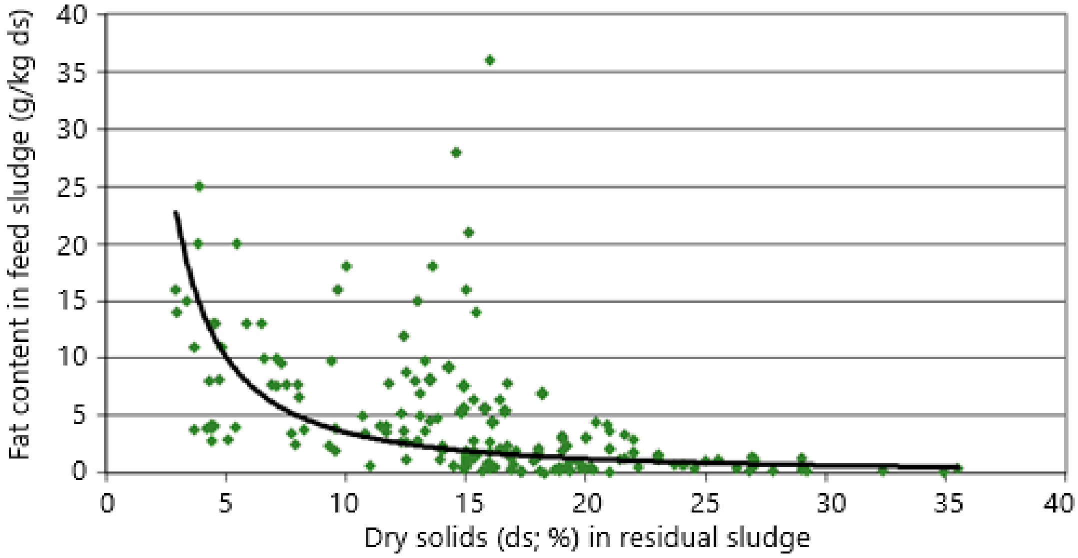

Figure 3. Correlation between fat and oil content in the feed sludge and dry solids content in the residual sludge [25].

2.3.3. Heavy Metals

The feed sludge can also contain high heavy metal content, depending on the industrial process generating the wastewater. Domestic sludge generally has low heavy metal content, even below the legal limits for sludge reuse [45,50]. However, if industries are connected to a municipal WWTP, this may result in increased heavy metal concentrations in the influent wastewater and in the produced sludge, which sometimes can inhibit reed growth in the STRB, and its quality often exceeds the legal limits for reuse in agriculture (Table 1). The drying of reed plants due to high nickel content in the residual sludge has been reported at a Danish WWTP that receives wastewater from a heavy industry.

Experiences from Danish STRBs after 10 and 20 years of continuous operation showed that the heavy metal content in the residual sludge is generally below the Danish and EU limit concentrations [32]. Heavy metals are mainly bound to particles in the residual sludge and the gravel media, so their mobility out of the STRB through drainage is limited [40,45,51–53]. A research study in pilot STRBs indicated that the gravel substrate is the main heavy metal sink [50]. The accumulation in the residual sludge layer and also the plant uptake were very low, while less than 16% of the heavy metal mass left the bed through drainage [50].

2.3.4. Nutrients

The residual sludge from an STRB is considered a valuable fertilizer, due to its high nutrient, i.e., nitrogen and phosphorus, content [45,54]. Nitrification and denitrification are the main microbial processes that transform and reduce nitrogen during the operation period [40]. A small amount of nitrogen also leaves the system through drainage, mainly as nitrate, and, thus, returns to the WWTP inflow. In addition, it has been observed that the total phosphorous concentration tends to increase in the residual sludge [45,52], as a result of organic matter mineralization. A small fraction of phosphorous is subjected to interactions with iron and other constituents and is thus bound in the residual sludge matrix.

2.3.5. Hazardous Organic Compounds

Sludge may contain a range of hazardous organic compounds, e.g., polyaromatic hydrocarbons (PAHs), di-2-ethylhexyl-phthalates (DEHPs), nonylphenol/nonylphenol ethoxylates (NPEs), and linear alkyl benzene sulfonates (LASs), which originate from coal and tars, lubricating oil additives, and detergents. Sludge treatment in STRBs results in the mineralization of these compounds [6,11,12,52,53]. The long operation period of STRBs, which can exceed 10 years, provides adequate time for microbiological and abiotic processes to effectively mineralize and decrease the contents of most hazardous organic compounds. Even for a shorter period of 3–6 months, significant reductions have been observed. Such processes have not been detected in conventional mechanical dewatering methods, e.g., centrifugation [11,45,53].

A previous study on the mineralization of LAS and NPE in sludge treated in an STRB reported 98% LAS and 93% NPE degradation under aerobic conditions [11], indicating that limited oxygen availability affects the degradation of organic compounds. Oxygen inflow into the sludge significantly enhanced LAS and NPE mineralization; on the other hand, mineralization under anaerobic conditions was very limited. The same study reported 60% and 32% reductions of DEHP and PAH, respectively [11,14]. The organic compounds were not only mineralized in the upper parts but through the whole depth of the residual sludge layer. Trials with anaerobically digested sludge (representing sludge after mechanical treatment) indicated a partial degradation of LAS, NPE, DEHP, and PAH in the top sludge layer (0–20 cm), while below this depth, it was observed that these compounds were not degraded [11].

3. Case Studies of Pilot and Full-Scale STRBs

3.1. Industrial Sludge with High Fat Content (Denmark and Sweden)

Table 2 shows different STRB systems that treat sludge from WWTPs that receive large wastewater inflow from various industries: the Tinglev STRB (abattoir), Kolding STRB (abattoir), Skagen pilot STRB (fish-industry), and Skive STRB (abattoir) in Denmark and a pilot STRB in Kristianstad, Sweden, that receives wastewater from the food processing industry, i.e., dairies, abattoirs (20–25%), chicken farms, and others. The sludge in these systems is characterized by a high LOI (65–76% ds), and high fat (15,000–30,000 mg/kg ds) and oil (2300–7000 mg/kg ds) contents. Table 2 also presents the respective dewatering results [53]. The high fat and oil content affected the dewatering process; the observed maximum infiltration rate was almost ten times lower (0.001–0.004 L/s/m^2) than the one in the Helsinge STRB in Denmark treating domestic sewage sludge (0.015–0.020 L/s/m^2) (Figure 4). It is reported that the treatment of sludge with LOI between 50 and 65% results in a maximum infiltration rate between 0.008 and 0.020 L/s/m^2 [38]. A high content of fats and oil in sludge often results in low dewatering that is not completed between two consecutive loads. Thus, the duration of the resting period is not long enough in between loads, which creates an anaerobic wet residual sludge.

Table 2. Dewatering efficiency of various STRBs in Denmark and Sweden treating sludge with high fat contents (P = pilot, F = full-scale).

STRB	Main Wastewater Origin	Infiltration Rate (L/s/m^2)	Fat Content in Feed Sludge (g/kg ds)	Dry Solids (ds) (%)		Loss on Ignition (LOI) (%)	
				Feed Sludge	Residual Sludge	Feed Sludge	Residual Sludge
Tinglev (F)	Abattoirs	0.002–0.005	21	0.4–0.6	10–15	75	70
Kolding (F)	Abattoirs	0.002–0.008	30	0.5–1.0	15–25	65	60
Skive (F)	Abattoirs	0.001–0.004	15	0.8–1.2	2.9–7.1	76	-
Skagen (P)	Fish industry	0.001–0.003	16	0.5–3.0	5–14	75	80
Kristianstad (P)	Dairies, abattoirs, chicken farm and others	0.003–0.020	29	0.5–2.5	8–14	70	75

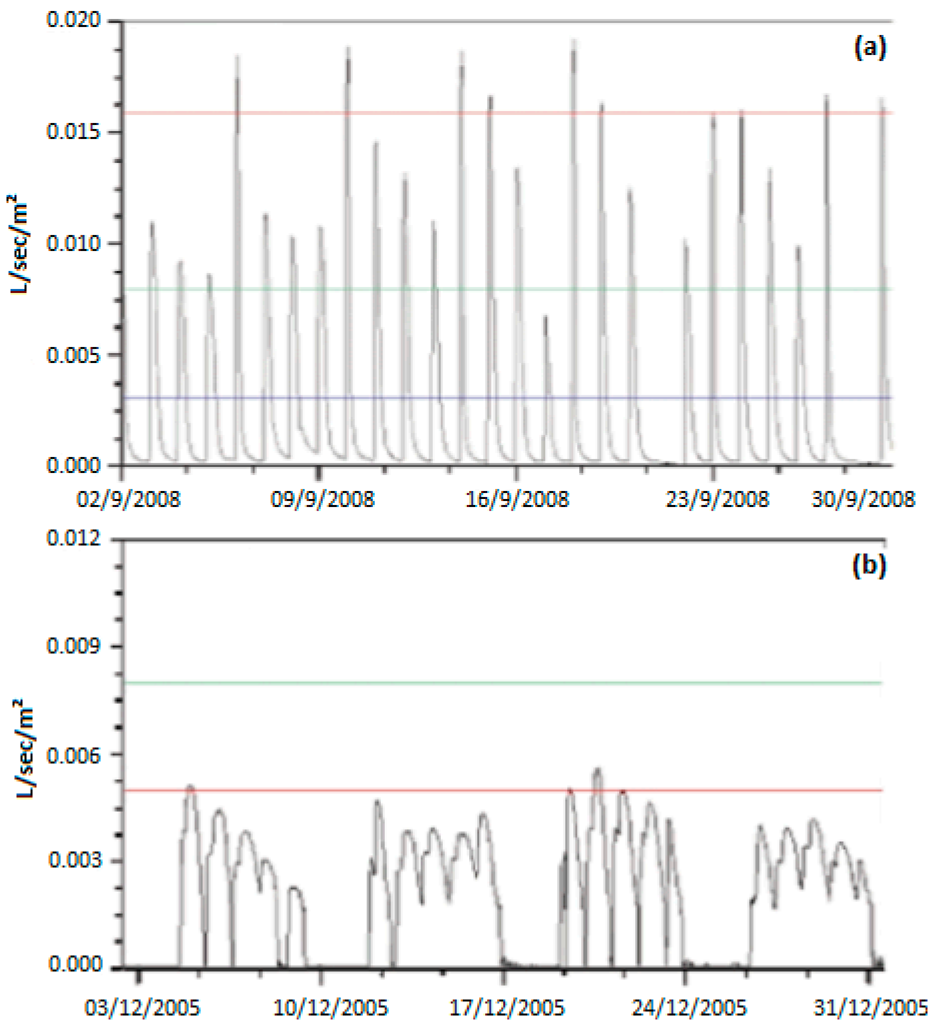

Figure 4. Infiltration rate curves at the (**a**) Helsinge STRB (domestic sludge) and (**b**) Tinglev STRB (industrial sludge) in Denmark [53].

3.2. Industrial Sludge with High Nickel Content (Denmark)

Feed sludge quality should be monitored on a regular basis to measure any potentially harmful pollutant levels. This is particularly important for heavy metals in order to prevent the residual sludge's application on agricultural lands if the national limits are exceeded, and the decision to dispose it to a landfill or incinerate it [45]. Excess heavy metal content could also negatively affect plant growth due to the phytotoxicity imposed on reeds, for example, by a nickel (Ni) content above 5 mg/kg ds.

The STRB in Stenlille (Denmark) that received sludge with a high Ni content showed affected reed plants (*Phragmites australis*) producing thin yellow new shoots (Figure 5) [53]. Figure 6 shows that the Ni content in the feed sludge was several times higher than the national Danish limit (i.e., 30 mg/kg ds; Table 1). The reed biomass at that STRB had a Ni concentration of 9.7 mg/kg ds, while the Ni content at 0–7, 7–14, and 14–21 cm depths in the residual sludge layer was 110, 150, and 80 mg/kg ds, respectively. Thus, in order to obtain good and green vegetation and, thus, a well-operating STRB, the Ni concentration in the feed sludge must be reduced either at the source or at the upstream WWTP. In the mentioned STRB (Figure 5), the industry responsible for the Ni contents in the wastewater was shut down in 2011; thus, plant coverage was re-established [53].

Figure 5. Yellow reeds and poor coverage in an STRB (Stenlille, Denmark) loaded with sludge rich in nickel (courtesy of Orbicon).

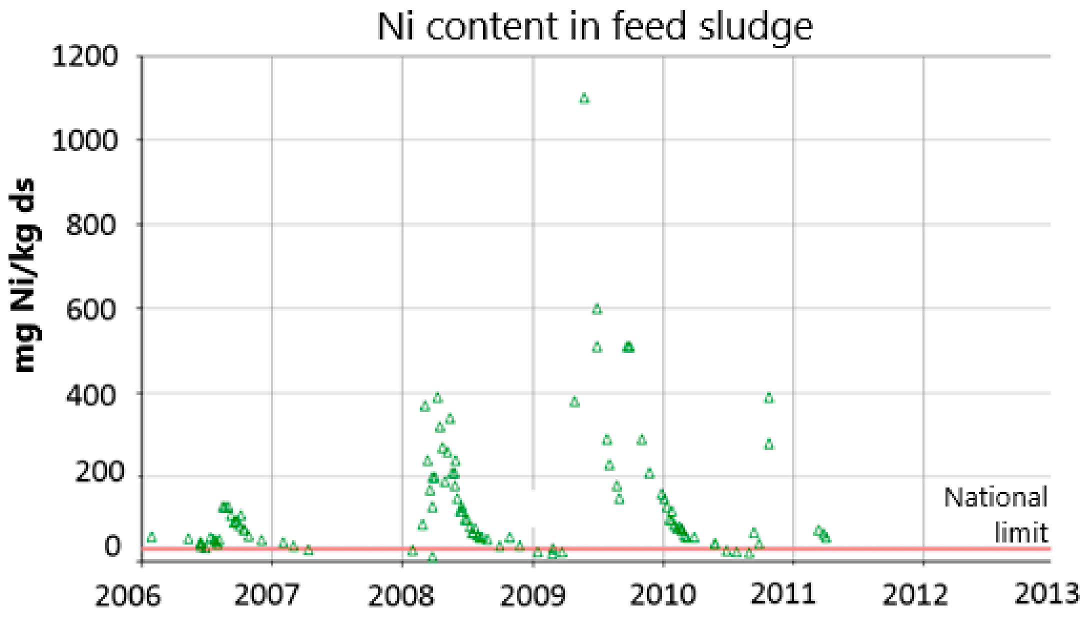

Figure 6. Nickel concentration (mg Ni/kg ds) in the feed sludge at an STRB in Stenlille (Denmark) [53]. The red line represents the Danish national limit for Ni in sludge recycled in agriculture (30 mg Ni/kg ds).

3.3. Sewage Sludge with High Chromium Content (Greece)

A large research project consisted of thirteen pilot STRBs that were built, operated, and monitored in Xanthi (northern Greece) for three years, treating surplus activated sludge (SAS) from a nearby WWTP in Komotini. Three of these pilot beds (Figure 7) received SAS spiked with chromium (Cr) to simulate the Cr content found in sludge produced during tannery wastewater treatment. Each pilot bed was a cylindrical plastic tank (height, 1.5 m; surface, 0.57 m^2) [29,55] and contained three porous medium layers (from bottom to top): a 15 cm cobble drainage layer (d_{50} = 90 mm), 15 cm medium gravel layer (d_{50} = 24.4 mm), and 15 cm fine gravel layer (d_{50} = 6 mm). The cobble layer contained drainage pipes connected to the atmosphere through vertical polyvinyl chloride (PVC) pipes open at the top. The gravel was obtained from a nearby riverbed. The pilot beds were planted with indigenous common reeds (*Phragmites australis*). The three pilot beds (A, B, and C) received three different SLRs, i.e., 75, 60, and 30 kg ds/m^2/year, respectively [30]. The feeding cycle consisted of one week of loading followed by 3 weeks (wintertime) or 1–2 weeks of resting (summertime). The SAS had an average ds content of 3.1% ds and volatile solids (VS) of 73.7% ds after thickening [56]. After almost 3 years of continuous loadings, the beds were left to rest for a period of 6 months without loadings (mostly in warmer months, June–October), during which regular samplings and monitoring continued.

Figure 7. Picture of the pilot STRB in Xanthi (northern Greece) treating activated sludge with a high Cr content.

The Cr content in the normal SAS was 276 mg/kg ds, but after the Cr addition, it increased to 5002 mg Cr/kg ds [48]. The dewatering efficiency of the three pilot STRBs exceeded 96% in terms of sludge volume reduction, indicating that the dewatering process was not affected by the addition of Cr [31]. However, the TS and VS contents were up to 10% and 2% lower, respectively, compared to those in other beds receiving the same SLR and SAS without added Cr. The Beds B and C receiving the two lower SLRs showed lower produced reed biomass values and lower evapotranspiration values, but the Bed A with the higher SLR did not show such changes [56]. This implies that the larger volume of sludge and, thus, water available for the plants could compensate, in a way, the possible effect of Cr addition. It should be noted that the plants did not show any visible toxicity signs in either of the three beds (e.g., yellow leaves), although it was obvious that the plant density and reed height in Bed C (low SLR) were smaller to those in the other two beds.

The Cr accumulation rate was high in the residual sludge, and after 2.5 years of operation, it reached 3463, 3625, and 3322 mg/kg ds in Beds A, B, and C, respectively [50]. During the final 6-month resting phase, the Cr content was further increased, reaching 8604, 8042, and 7686 mg/kg ds, respectively, due to the further mineralization and reduction of the residual sludge volume. Higher Cr content was found at the bottom part of the residual sludge layer in all three beds than at the top [48]. It was also found that the addition of Cr affected the time needed for the residual sludge to reach good stability values in Bed A receiving the high SLR, resulting in a slower degradation rate and an inhibition of the microbial respiration activity [57]. However, in the two beds receiving lower SLRs, sludge stabilization was not significantly affected by the high influent Cr content.

A higher Cr concentration was also found in the drained water, compared to the other beds receiving SAS without Cr addition, indicating that a larger portion of Cr leaves the bed through drainage. Cr losses in the drained water were found to be the main fraction (42–48%) in the Cr mass balance. Accumulation in the residual sludge accounted for 26–34% of Cr losses, followed by adsorption to gravel media (20–25%) [50]. In general, the pilot STRB managed to handle the excessive Cr load without showing any visible toxicity signs. However, the EU legal limit values (Table 1) were quickly exceeded, prohibiting a potential reuse of the residual sludge.

3.4. Water Works Sludge (England)

The handling of settled coagulated sludge from water works (WW) represents a big concern for the European water industry [58]. Generally, this type of sludge presents poor dewatering properties that hinder its easy beneficial reuse. WW sludge is a by-product of freshwater purification processes that has a low solids content, namely river and lake water and/or groundwater purification. Coagulation with, for example, aluminium sulphate, polyaluminium chloride, ferric sulphate, or ferric chloride is applied to remove impurities, resulting in the production of sludge that is usually sticky, not easy to handle, and often has an unpleasant odour. One management option is landfill disposal, but this is not a cost-effective practice [58]. Thus, its onsite dewatering or its transportation to the nearest WWTP is typically preferred. Although mechanical methods are usually applied for WW sludge dewatering, pilot and full-scale STRBs have been tested over the last 10 years.

WW sludge generally has a low solids content (0.1–0.4% ds), i.e., lower than the solids content in a typical activated sludge (0.3–0.6% ds) from WWTPs. It also has a high iron or aluminium content, due to the upstream coagulation process that usually utilize ferric- or aluminium sulphate/chloride. The organic matter, oil, and fat contents are generally low (<1000 mg/kg ds) [58,59].

Table 3 presents general information on the STRBs in England for WW sludge dewatering. The STRB at the Hanningfield Reservoir in Essex (Northumbrian Water) is located at an approximate distance of 3 km from the WW facility and was built in 2012 with a treatment capacity of 1275 t ds/year (Figure 8a; Table 3). This system is, today, the world's largest full-scale STRB facility, with 16 basins covering an area of 4.5 hectares. Pilot STRB beds (Figure 8b,c) were first tested between 2008 and 2013 before the construction of the full-scale system [53,60]; six pilot beds of 20 m^2 each were installed to study the dewatering properties of the sludge from the WW. The pilot bed design followed that of a full-scale STRB.

Table 3. STRBs in England for water works sludge treatment (P = pilot, F = full-scale, FS = ferric sludge, AS = alum sludge, WW = Water Works) [45,53,60].

Water Works Facility	Period	No. of Beds	Total Treatment Area (m^2)	Sludge Type
Hanningfield WW (P)	2008–2013	6	120	FS
Hanningfield WW (F)	2012–2014	16	42,500	FS
Lumley WW (P)	2010	3	3	AS
Whitacre WW (P)	2015–2016	3	3	FS

At the Whitacre WW (Severn Trent Water), sludge was treated in a pilot STRB (Table 3). At that facility, the de-sludging and washing of the pulsator clarifiers produces mineral ferric sludge, since the previous water treatment includes coagulation with ferric sulphate. The ferric sludge was stored in a plastic tank and then loaded onto the pilot STRB over a five-month period in 2015. The pilot STRB setup included three beds of 1 m^2 surface area each.

Figure 8. (**a**) Full-scale and (**b**,**c**) pilot-scale STRB systems [38,59] at Hanningfield (England) for water works sludge dewatering (courtesy of Orbicon).

3.4.1. WW Sludge and Drained Water Quality

The feed sludge of both the Whitacre and Hanningfield WW had a dry content between 0.1 and 0.5% (Figure 9) and a suspended solids content between 100 and 8000 mg/L (Table 4), respectively. As Figure 9 shows, there is a wide range of the ds applied on the beds; hence, it is crucial to know the ds percentage in each load so that the exact areal load to be applied can be calculated (kg ds/m^2/year). The use of an average ds value may result in an overestimated load in some beds and underestimated in others. Moreover, the sludge from the two WW had a relatively low organic content (i.e., low LOI), between 20 and 40% ds (Table 4). It should be noted that the respective figures for sewage sludge are usually between 50 and 70%.

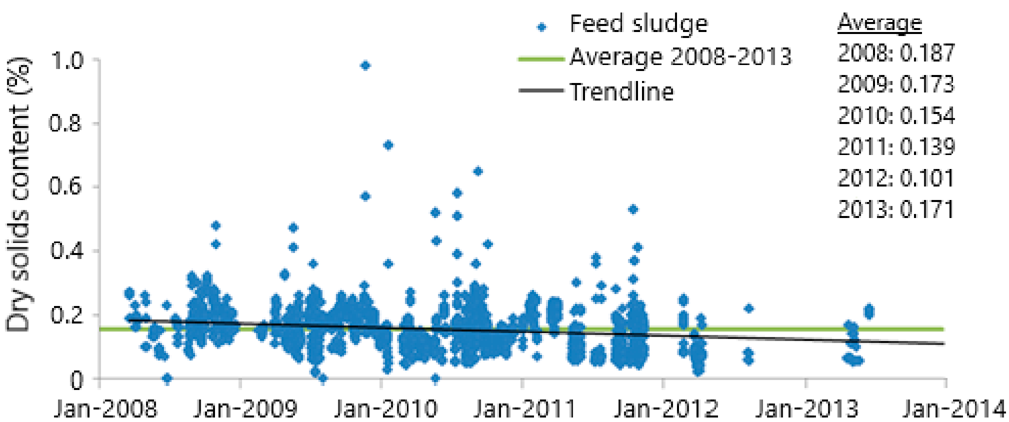

Figure 9. Dry solids (%) in the feed sludge at the Hanningfield WW [53].

Table 4. STRB feed sludge characteristics at the Whitacre and Hanningfield WW (England). Both facilities utilize ferric sulphate as a coagulant (P = pilot, F = full-scale, WW = Water Works) [53,58,60].

Feed Sludge		Whitacre WW (P)	Hanningfield WW (P + F)	Range
Monitoring Period:		**Autumn 2015**	**2008–2013**	
Parameter	**Unit**	**Aver. (*n* = 2)**	**Aver. (*n* > 25)**	
Dry solids	%	0.3	0.2	0.1–0.5
Suspended solids	mg/L	2630	1262	100–8000
Loss on ignition	%	40	23	10–40
pH	-	7.3	7.4	6.8–8.7
Fat and oil	g/kg ds		0.60	0.010–2.4
Total iron as Fe	g/kg ds	259	233	100–400
Total aluminium	g/kg ds	0.43	0.41	0.1–3
Total nitrogen (TN)	g/kg ds		2.3	1–14
Total phosphorous (TP)	g/kg ds		6.96	1.5–11
Phosphate (as P)	g/kg ds	7.24		2000–8000
Chloride	g/kg ds	16,30	41.6	15–45
Total calcium	g/kg ds	33.6	98.1	32–290

The feed sludge at Hanningfield WW had a very low fat and oil content (average, 0.600 g/kg ds) but high iron content (average, 250 g/kg ds). The pH range was within the acceptable limits for plant growth. The presence of nutrients in the sludge implies that the use of fertilizer can be limited or even avoided if the treated sludge is reused. The drained water at both WW had significantly low dry solids, suspended solids, iron, and total phosphorous contents (Table 5).

Table 5. Drained water characteristics in STRB at the Whitacre and Hanningfield WW (England) (P = pilot, F = full-scale, WW = Water Works, BOD5 = Biochemical Oxygen Demand, COD = Chemical Oxygen Demand) [53,58,60].

Drained Water		Whitacre WW (P)	Hanningfield WW (P + F)	Range
Monitoring Period:		**Autumn 2015**	**2008–2013**	
Parameter	**Unit**	**Aver. (*n* = 3)**	**Aver. (*n* > 25)**	
Dry solids	%	0.06	0.05	0.001–0.06
Suspended solids	mg/L	93	0.01	0.001–0.05
pH	-	7.9	7.7	7.0–8.0
BOD5	mg/L	5	2.4	1–36
COD	mg/L	44	33	3–380
Total iron as Fe	mg/L	29	4.5	0–120
Total phosphorous as P	mg/L	0.1	0.2	0–4.6
Total nitrogen as N	mg/L	-	3.3	0–10
Chloride	mg/L	52	74	50–100

3.4.2. Sedimentation and Capillary Suction Time

The dewaterability of WW sludge can be evaluated via a simple and easy sludge sedimentation test. The low fat and oil content in the sludge from Hanningfield WW resulted in a relatively rapid sedimentation of the suspended solids, and a settled sludge layer (8–10 cm) was formed after 30 min [53]. The liquid phase (i.e., above the settled sludge) is transparent without any colouring. The sludge sedimentation properties should be regularly tested during the experimental period to detect any changes at the WW.

The capillary suction time (CST) provides another good indication of the sludge dewatering properties, measuring how fast the sludge wets a filter paper. A CST between 10 and 100 s indicates a good dewaterability. The CST measured for WW sludge is usually higher compared to that for WWTP sludge, indicating that this sludge presents more difficulties in dewatering. Nevertheless, the dewatering process was not affected by the higher CST values of the WW sludge and the cracks on the sludge layer surface [53]. The CSTs at the Hanningfield and Whitacre WW were both around 2–4 times (30–110 s) higher than the CST of the surplus activated sludge (10–40 s) (Figure 10). On the other hand, the digested WWTP sludge can have CST values higher than 2000 s. These sludge types typically possess higher fat and oil contents.

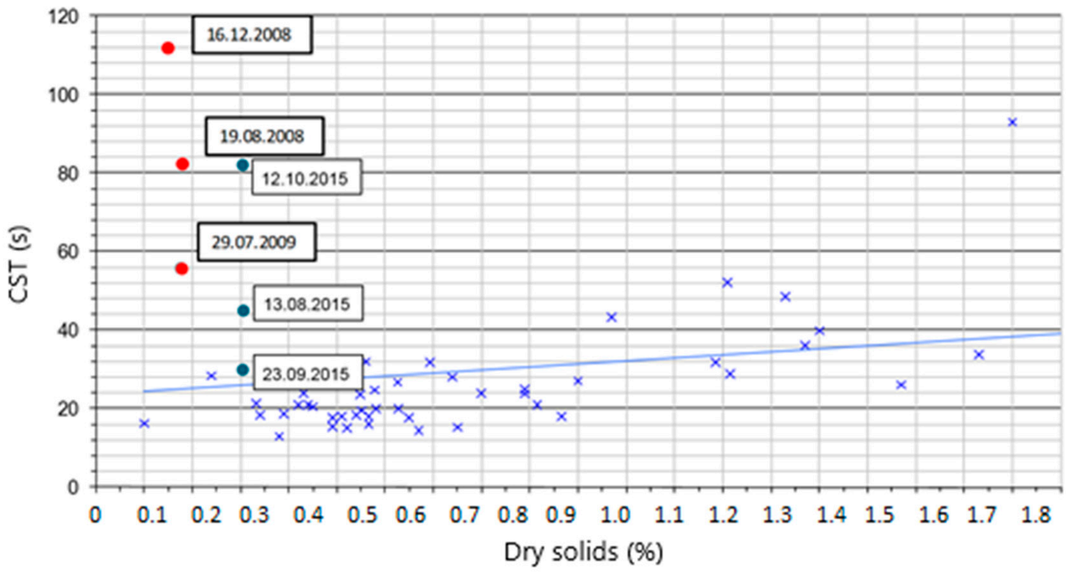

Figure 10. Capillary suction time (CST) of surplus activated sludge (blue X) and sludge from the Hanningfield WW (red dots) and Whitacre WW (blue dots) [53].

3.4.3. Water Works Sludge Volume Reduction and Residual Sludge Development

After each sludge load, dry solids accumulate on the bed surface as residual sludge, whereas most of the water content drains vertically through the residual sludge layer, and the residual sludge volume is also reduced via evapotranspiration. The sludge volume in an STRB is typically reduced at high levels due to the low solids content of the raw sludge. Monitoring of the loading phase over 5.5 months of the pilot STRB at the Whitacre WW showed that the sludge volume reduction reached 97–98%. As a result of the intensive feeding cycles with four days of loading, e.g., in Bed 3 from 23 to 27th November (Figure 11), the residual sludge layer thickness increased fast, while it was markedly decreased thereafter during the resting period due to drainage and evapotranspiration [53].

A similar reduction of the sludge volume (>98%) after 3–5 days of sludge application was observed at the Hanningfield pilot STRB. Both pilot and full-scale systems for WW sludge indicate that the ds content in the feed sludge (approx. 0.1–0.2%) is 100–200 times concentrated in the residual sludge layer, reaching a content between 25 and 40% [58]. A higher ds content (>50%) in the residual sludge was measured in some pilot beds at the Hanningfield WW.

Furthermore, as already mentioned, the visual status of the residual sludge layer serves as another indication of the sludge dewaterability. After sludge application, the WW sludge surface quickly shows cracks (Figure 12) as a result of the low fat and oil and organic matter contents. On the other hand, some types of sewage sludge will not crack so easily, especially sludge from WWTPs receiving dairy or abattoir wastewater with a high fat and oil content.

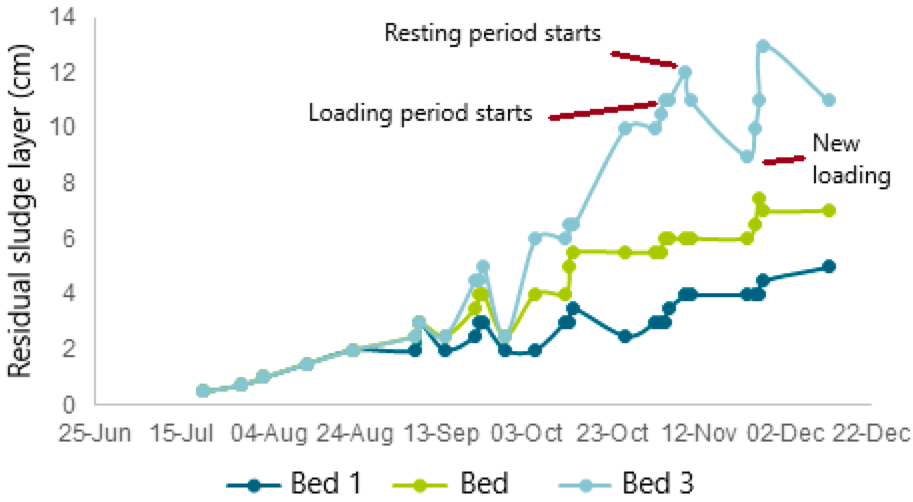

Figure 11. Residual sludge layer thickness (cm) in Beds 1–3 at the pilot STRB at the Whitacre WW during July–December 2015 [53].

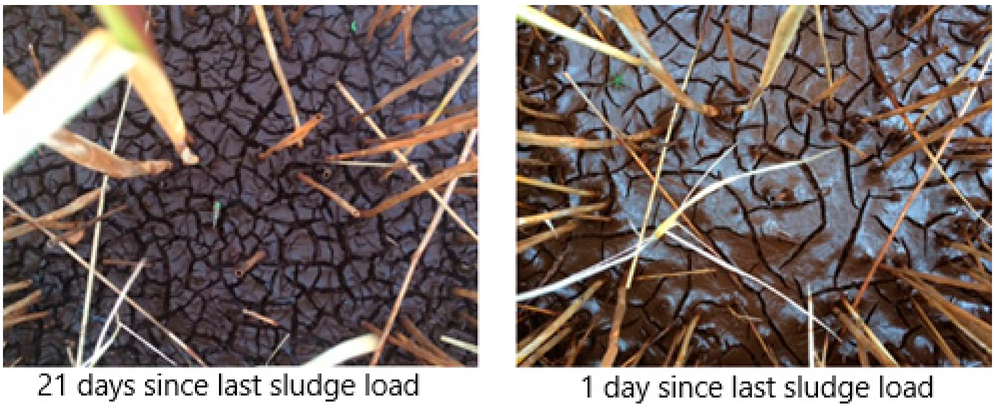

Figure 12. Pictures of the residual sludge surface at the Whitacre pilot STRB at the end (**left**) and at the start of the resting period (**right**) (courtesy of Orbicon).

3.4.4. Infiltration Rate

Most of the water content in each sludge load drains vertically through the residual sludge layer and the filter media and reaches the drainage network. The water flow curve is a useful parameter that should be monitored during the STRB operation (Figure 13). A decrease in the peak flow (L/s/m^2) over time after each resting period or a decline in the flow curve that does not reach zero in the first part of the resting period indicates that the STRB is not working properly. The drained water curves from the Whitacre and Hanningfield pilot STRBs are similar to the drained water curves usually seen in full-scale STRBs for domestic wastewater sludge: there is a first peak that within a few hours declines towards zero flow (Figure 13). The highest infiltration rate was between 0.015 and 0.03 L/s/m^2. The dewatering process at the Hanningfield pilot and full-scale STRB was good without surface clogging or water ponding. The drained water quality showed that there was no bypass of sludge in the pilot beds [53,58,60].

Generally, the results from pilot and full-scale STRBs receiving WW sludge show that this sludge type can be effectively treated in an STRB if they are properly constructed and operated.

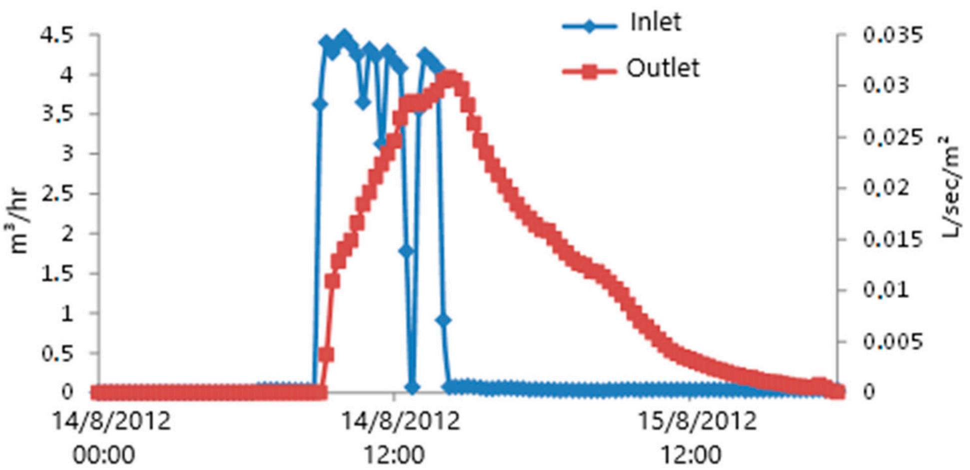

Figure 13. Pilot STRB at Hanningfield WW: four sludge loads during the same day (blue curve, m^3/h) and the dewatering profile (red curve, $L/s/m^2$) [53].

3.5. Overall Evaluation

Generally, the use of STRBs for industrial sludge dewatering has been proved to be a technically and economically feasible alternative to mechanical methods, providing a series of benefits as shown in Table 6 [1,61]. The main advantage of STRBs in industrial sludge dewatering is the significantly lower operation and maintenance costs compared to those of conventional technologies. It is reported that industrial sludge management could account for even 50% or more of the overall wastewater treatment costs when using mechanical technologies, mainly due to the huge energy input required [37,49,62,63], which is not the case for STRBs. Current experience from pilot and full-scale STRB systems dictates that sludge from WW can be treated in STRBs, if the contents of organic matter, fats, and oil are not too high. Reeds can be established in these systems, and their growth is not inhibited by this sludge type, e.g., ferric sludge. STRBs for WW sludge demonstrated a good dewatering capacity, as implied by cracks on the residual sludge surface once the water was drained out of the system. The SLR applied during the trials was between 30 and 45 kg ds/m^2/year, and the ds content of the residual sludge reached 40% in pilot beds. The drained water from the beds showed a maximum infiltration rate of 0.02–0.03 L/m^2/s after loading, and then declined fast over the following few hours. On the other hand, the dewatering of biological or alum sludge through mechanical processes results in a solids content that does not usually exceed 15–20% [43,62,64]. Thermal processes can deliver higher solids contents, but the high energy required for these systems makes them often not financially feasible and also technically challenging [64,65].

Table 6. Overall evaluation of STRB and mechanical methods for industrial sludge dewatering.

Criterion	STRB	Mechanical Systems
Land area demand	High	Low
Investment cost	Moderate/high	Moderate
Operation and maintenance cost	Low	High
Power input demand	Minimum	High
Use of chemicals, e.g., polymers	No	Typically required
Quality of final biosolids	High	Low
Life expectancy of main components (re-investment interval)	20–30 years	5–10 years
Need for skilled operators	No	Yes
Nuisance (mosquitos and odour)	No/minimum	Moderate/high
Downtime due to, for example, failure or repair	None	To be expected/frequent
Climate change impact	Positive (carbon sink)	Negative
Aesthetic appeal	High	Low
Biodiversity enhancement	Yes	No
Corporate social responsibility value	High	Low

The high organic solids content in feed industrial sludge leads to lower ds content and anaerobic conditions in the residual sludge layer. Along with organic matter, the contents of fat and oil and heavy metals are the main parameters that should be monitored and tested when sludge of industrial origin is to be treated. It is advised to control the fat and oil content in the feed sludge at the WWTP by enhancing its upstream removal, to reduce the amount that reaches the STRB. Moreover, an STRB trial is suggested before the implementation of a full-scale system in order to evaluate the sludge dewaterability using the STRB technology and optimize the system performance and operation, e.g., in terms of the applied SLR and required number of beds.

Since heavy metals are conservative pollutants and cannot be degraded in an STRB system, they accumulate in the residual sludge layer and the porous media. Elevated heavy metal concentrations can be found in some agro-industrial wastewater, such as abattoir effluents, which are usually discharged into a municipal WWTP. During the operation of an STRB system, the heavy metal content may increase in the bottom sludge layers that contain sludge from older applications, due to the mineralization of organic solids [45,50]. In some cases, the heavy metal content may exceed the respective legal standards for land application [49,52]. However, it has also been reported that the residual sludge quality in STRBs, even after 20 years of operation, can comply with the Danish and EU regulations, considering the heavy metal content in relation to phosphorous content [45].

Moreover, no iron was detected in the gravel layers of STRBs treating sludge from WW, while the iron content in the drained water was low over a 5-year trial. This implies that iron is retained in the residual sludge layer and does not clog the drainage pipes. A high iron content in the feed sludge means that the establishment of aerobic conditions in the residual sludge is crucial for preventing iron precipitation as ochre that might create clogging issues.

4. Conclusions

STRBs are robust treatment systems that can dewater various sludge types. The feed sludge quality is an important factor that affects sludge dewaterability. Besides the various environmental and economic benefits of this sustainable technology, sludge mineralization and stabilization take place in STRB systems with time, e.g., the reduction and degradation of hazardous organic compounds. Such processes do not occur with conventional mechanical methods. Industrial sludge types, e.g., sludge from WWTPs that receive wastewater from industries (e.g., the food industry and agro-industries), as well as ferric sludge from water works, can be effectively treated in STRBs. Pilot and full-scale STRBs under cold and moderate climates have demonstrated that these systems can provide not only satisfactory dewatering but also the possibility for further sludge reuse in agriculture, contributing, in this way, to a more circular sludge management.

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