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Review

Sludge Treatment Reed Bed under different climates: A review using meta-analysis

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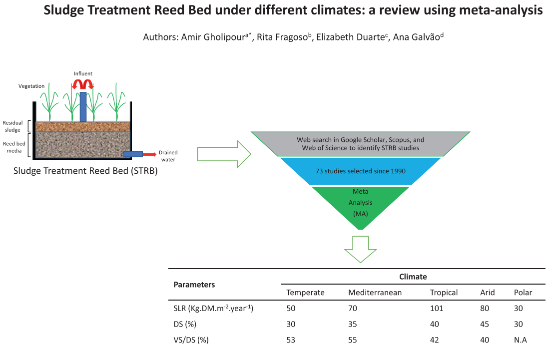
HIGHLIGHTS

- Meta-Analysis for Sludge Treatment Reed Bed is presented through 73 published papers since 1990.
- The recent development of the system is identified.
- A list of plant species based on climate conditions is presented.
- STRB removal efficiency for accumulated sludge and drained water is analyzed.
- Average SLRs for Temperate, Mediterranean Temperate, and Tropical climates are proposed.

GRAPHICAL ABSTRACT



Sludge Treatment Reed Bed under different climates: a review using meta-analysis

Authors: Amir Gholipour[a*], Rita Fragoso[b], Elizabeth Duarte[c], Ana Galvão[d]

Parameters	Climate				
	Temperate	Mediterranean	Tropical	Arid	Polar
SLR (Kg.DM.m^{-2}.year^{-1})	50	70	101	80	30
DS (%)	30	35	40	45	30
VS/DS (%)	53	55	42	40	N.A

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ABSTRACT

Sludge Treatment Reed Beds (STRBs) have been used worldwide over the past few decades. This review aims to overarchingly identify and appraise the currently available knowledge of STRB technology and discern climatic patterns through Meta-Analysis (MA). We systematically searched Google Scholar, Scopus, and Web of Science databases (up to Dec 2021) via a combination of keywords to identify English-language studies published in peer-reviewed journals. Of 142 potential articles, 73 studies met the present review objectives and inclusion criteria. Four STRB classifications including typical STRB, earthworm STRB, Sludge Treatment Electro Wetland (STEW), and earthworm STEW were found since 1990. The data and information on STRBs' configuration, operational parameters in terms of location, type of sewage sludge, study scale, Sludge Loading Rate (SLR), Dry Solid (DS), the proportion of Volatile Solid to DS (VS/DS), and their association with the feeding and resting modes were extracted from the selected articles. The analysis was focused on the interconnections between operational parameters and system efficiency for Temperate type 1 (low intensity of solar radiation), Temperate type 2 (high intensity of solar radiation), and Tropical climates. Based on MA, we found the average SLRs of 50, 70, and 101 Kg.DM.m^{-2}.year^{-1} for Temperate type 1, Temperate type 2, and Tropical climates respectively, and DS during the feeding of 33 %, 35 %, and 40 %. A qualitative comparison of Arid and Polar climates was also performed given the reduced number of studies available in these climates. The volume of the sludge reduced was 60 % higher and the height of accumulated sludge was annually 2 cm in the

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Acronyms: AHTN, 6-Acetyl-1,1,2,4,4,7-hexamethyltetraline; ANOVA, Analysis and Variance; ARGs, Antibiotic-Resistant Genes; AZM, azithromycin; CWs, Constructed Wetlands; COD, Chemical Oxygen Demand; CIP, ciprofloxacin; DS, Dry Solids; DEHP, Diethyl Hexyl Phthalate; DM, Dry Matter; DB, Drying Bed; ET, evapotranspiration; GHGs, Greenhouse Gases; GWP, Global Warming Potential; HMs, Heavy Metals; HHCB, 2-benzopyran; LCA, Life Cycle Assessment; MA, Meta-Analysis; MES, microbial electrochemical system; NBS, Nature-Based Solutions; O&M, Operation and Maintenance; OTNE, Octahydro-Tetramethyl-Naphthalenyl-Ethanone; PCPs, Personal Care Products; STRB, Sludge Treatment Reed Bed; STEW, Sludge Treatment Electro Wetland; SLR, Sludge Loading Rate; SAS, Surplus Activated Sludge; TOC, Total Organic Carbon; TP, total phosphorus; TKN, Total Kjeldahl Nitrogen; TN, Total Nitrogen; TK, Total Potassium; TSS, Total Suspended Solid; VS, Volatile Solids; WWTP, Wastewater Treatment Plant.

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earthworm STRBs, and STEWs compared to typical STRBs, which was 6 cm annually in Tropical climates. Correlation analysis, media characterization, list of plant species, and the removal efficiency of STRBs in the residual sludge and leachate are mentioned as well.

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1. Introduction

In Wastewater Treatment Plants (WWTPs), solid-phase treatment is of paramount importance due to the bulk volume of sludge produced (between 1 and 10 % of influent volume), which needs to be addressed (Nielsen, 2003). Sludge extraction and dewatering are currently conducted in most WWTP globally to achieve safe disposal to the environment (Yoshida et al., 2013; Cieślik et al., 2015). Hazardous materials such as toxic components are the main challenges causing threats to the environment and putting human health at risk (Cusidó and Cremades, 2012). Owing to toxic components, sewage sludge has the potential to degrade soil quality, contaminate surface and groundwater resources, and aquifers, threaten aquatic habitats and ecosystem of organisms put biodiversity at risk, and cause diseases outbreak (Kacprzak et al., 2017). On the other hand, the sewage sludge or “bio-solid” is an invaluable resource containing nutrients and beneficial bacteria (gram-positive bacteria) as well as gases, e.g., methane (Epstein, 2002).

A wide range of mechanical solutions for sewage sludge dewatering has already been applied all around the world including belt filter presses, centrifuges, and chamber filter presses among others (Wang et al., 2010; Peeters, 2010; Almatin and Gholipour, 2019; Daee et al., 2019). Mechanical techniques typically involve high installation costs, high energy consumption, the need for specialized personnel, high operational and maintenance (O&M) costs, and poor dewatered sludge fertility. Moreover, they are infeasible to apply any locality and climate condition to provide environmental services (Brix, 2017). Nature-Based Solutions (NBS) are cost-effective technologies that can be considered as alternative methods for conventional techniques such as Sludge Treatment Reed Beds (STRBs) and drying beds (Uggetti et al., 2010). STRB technology is one of the applications of Constructed Wetlands (CWs) for wastewater treatment and management (Brix, 2017; Vymazal, 2011; Gholipour et al., 2020; Gholipour and Stefanakis, 2021).

STRBs can be easily applied to any scale and climate condition (Vymazal, 2011), and is a sustainable solution, which can benefit the environment in the long-term run. STRB system enriches aesthetically local landscape and provides habitats for a wide range of living organisms particularly migrant birds, contributing to biodiversity preservation and conservation (Lafortezza et al., 2018). STRB technology is an active scrubber in the reduction of air pollution and the mitigation of Greenhouse Gases (GHGs) in comparison with mechanical techniques (Liang et al., 2021). STRBs can also contribute to the alleviation of climate change effects and carbon sequestration by vegetation (Olsson et al., 2014).

To enhance STRB performance and develop the system design, several variations have been applied to the typical STRB design. STRB system has been used with the addition of earthworms (earthworm STRB) to enhance the performance in reed beds (Calderón-Vallejo et al., 2015; Chen et al., 2016; Hu and Chen, 2018; Hu et al., 2020). Energy harvesting through STRB is another application of STRB called Sludge Treatment Electro Wetland (STEW) by Wang et al. (2021) while the addition of earthworms together with STEW systems was tested called earthworm STEW (Zhong et al., 2021). Studies revealed that the highest power output (0.790 V of voltage and 0.229 Wm^{-2} of power density) of STEW can be achieved provided that an SLR of 125 kg $DS.m^{-2}$ $year^{-1}$ is considered (Wang et al., 2021). In another similar study, a combined system of STEW and earthworm was tested which could yield a voltage of 0.832 V and a maximum power density of 94.98 Wm^{-2} on the 5th day (Zhong et al., 2021). In addition, STRB has been coupled with a system of active aeration, intensified STRB, to enhance the dewatering and stabilization mechanisms (Plestenjak et al., 2021).

STRBs have been effective in the removal of different contaminants compared to mechanical systems in terms of final dry and volatile solids obtained (Uggetti et al., 2010). The fate of trace pollutants such as Heavy Metals (HMs), Personal Care Products (PCPs), and pharmaceuticals were reported in previous studies (Nielsen, 2007, Stefanakis and Tsihrintzis, 2012a, Chen et al., 2009, Wang et al., 2018, Kołecka et al., 2019, Arroyo et al., 2018; Kowal et al., 2021). In another study, HMs accumulation in the residual sludge layer was found low and increased with sludge layer depth, and plant uptake was low and <16 % as well (Stefanakis and Tsihrintzis, 2012a). PCPs such as fragrances HHCB, AHTN, OTNE, and Triclosan were degraded in an STRB system pilot study and reduced up to 20, 30, 70, and 70 %, respectively (Chen et al., 2009). Also, antibiotics including roxithromycin, azithromycin, oxytetracycline, and pharmaceuticals (non-steroidal anti-inflammatory drugs - ibuprofen, paracetamol, flurbiprofen, naproxen, diclofenac, and its metabolites) decreased in the STRB system (Wang et al., 2018; Kołecka et al., 2019). The study by Kołecka et al. (2019) showed that Ibuprofen and naproxen were completely removed, and diclofenac and its metabolites were found as chemicals more persistent to be removed. According to Wang et al. (2018), the reed and the media ventilation structure affect positively the removal of antibiotics. In a study of xenobiotic compounds of the PCPs, it was shown that the bactericide triclosan, fragrance OTNE and DEHP were reduced at least >30 % of their original concentration in different layers of the accumulated sludge while the polycyclic musk compounds HHCB, AHTN, and the primary metabolite of HHCB, i.e., HHCB-lactone did not degrade in 13 months of the pilot study (Chen et al., 2009). A study by Wang et al., on two antibiotics including ciprofloxacin (CIP) and azithromycin (AZM) showed that STRB had a better removal efficiency of antibiotics compared to the drying bed system. Time was found to be the factor that affects most the concentration of CIP and AZM in the accumulated sludge and after three years of operation, more than half of the antibiotics were removed. A study of Antibiotic Resistance Genes (ARGs) targeted five ARGs such as sul1, sul2, tetC, tetA, and ermB together with intI1, and 16S rRNA showed that STRB was effective at removing >73 % of all ARGs and intI1 and 16S rRNA were removed 73.5 and 78.6 %, respectively.

Helsinge STRB plant in Denmark was effective in the removal of pathogenic microorganisms including *salmonella*, *enterococci*, and *Escherichia coli* (*E. coli*) in which *enterococci* and *E. coli* reductions were log 5 and log 6 to 7, respectively (Nielsen, 2007). The bacteria population and biodiversity play important roles in the treatment performance as well (Arroyo et al., 2018; Kowal et al., 2021). In the study of Kowal et al. (2021), 80 % of the bacterial community was of the *Bacteroidetes*, *Proteobacteria* and *Firmicutes*, identified in the sequences read through 16S rRNA gene sequencing in domestic wastewater in Gniewino, Poland in an STRB system and a similar result was found in Zhong et al. study on earthworm STEW (2021). The biodiversity of the communities was also found diverse on the surface of the STRB system and on the bottom of a bed equipped with a passive aeration system. The most responsible and abundant organism is *Nitrospira* regulating nitrogen metabolism in the STRBs tested (Kowal et al., 2021). Arroyo et al. (2018) have investigated bacterial community composition, richness, diversity, and ordination in swine slurry fed over an STRB system via 16S rRNA gene high-throughput in which pH value was the crucial indicator of the community response mode.

As the result of the decomposition of organic matter, gases such as CO_2 and CH_4 emit from STRB into the atmosphere. The CO_2 flux of the Drying Bed (DB) was two times higher than that of STRBs and the Global Warming Potential (GWP) of CH_4 emissions in DB was less than that of STRBs. However, the GWP of DB and STRB systems was found to be much lower than values for mechanical dewatering techniques (Cui et al., 2015; Liang et al., 2021). Liang et al. found that annual CO_2-eq CH_4 during the loading period was higher than that during the resting period due to loads of sludge entering the system at once. The gases such as CO_2 generated from wastewater and sludge are considered climatic-neutral (IPCC, 2006).

Most previous STRB reviews defined STRB technology and the design aspects in a general view (narrative reviews) focusing on studies in Europe, as in Denmark and Poland, while other parts of the world were left uncovered (De Maeseneer, 1997; Zwara and Obarska-Pempkowiak, 2000; Nassar et al., 2009; Uggetti et al., 2010; Pandey and Jenssen, 2015). The recent reviews including the study of Bui et al. (2019) narrated a few studies of STRBs to draw a comparison while Elbaz et al. (2020) reviewed sludge filtration beds and Nielsen and Stefanakis (2020) reviewed the application of STRB for the industrial sector. Since STRB is an NBS mimicking natural processes, it is highly dependent on the climate condition, which was not considered thoroughly in the previous reviews. The present study systematically reviewed the variations of STRB technology in terms of design, operation, and dewatering performance through three decades of the published literature in Temperate, Tropical, Arid, and Polar climates classified via Köppen–Geiger climate classification (Beck et al., 2018). A Meta-Analysis (MA) of the extracted data on STRB technology was conducted, which as far as the authors know, is performed for the first time in the literature databases of STRB. Statistical comparisons between different climates and correlation analysis were performed between design and performance factors. Ranges of operating conditions for Sludge Loading Rate (SLR), Dry Solids (DS), and Volatile Solids (VS) were obtained. Feeding and resting modes of STRB, the volume of the sludge accumulated, and the volume reduced will be presented as well. Thus, the result of the MA can be used for the design and operation of STRB systems under each climate. Analysis of the reed bed media compositions, including filtration materials and the list of plant species used, are also documented in this review. A comparison of dewatering efficiencies between typical STRB, earthworm STRB, STEW, earthworm STEW, and intensified STRB are reported for the first time as well.

2. Materials and methods

2.1. Sludge Treatment Reed Bed (STRB)

Sludge Treatment Reed Bed system consists of several reed beds that are sequentially loaded by surplus sludge of WWTPs (Brix, 2017). Fig. 1 presents a typical system of STRB, consisting of three layers of natural cobbles such as coarse gravel, sand, and gravel and fine particles including drainage, main, and transition layers planted with the native plant (invasive reeds) (Uggetti et al., 2010). The raw sludge is fed over the reed bed and most solid particles are retained on the surface of the top layer. In the STRB design, a freeboard space on the top of the bed allows for the accumulation of sludge, which improves dewatering and stabilization through biochemical processes and other treatment mechanisms (Stefanakis et al., 2014). The liquid part drains down the system as leachate, which is collected through a drainage layer composed of course gravel and is discharged by an outlet pipe connected to a ventilation network.

STRB operation requires the application of consecutive loads of sludge with an interval in between along with resting periods. A schematic representation of STRB operation periods for sludge dewatering is shown in Fig. 2. The selected SLR (Kg, DS/m^2.year) was applied over the whole year of the operation period with each feeding duration consisting of a different load with intervals defined according to climate conditions (Brix, 2017).

The interval between two consecutive feedings is called operational rest and when the freeboard of STRB is filled with accumulated sludge, a period called final rest is established to minimize sludge volume, increase DS

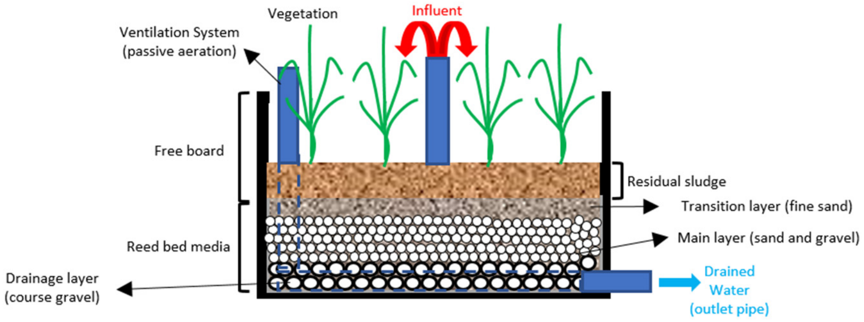


Fig. 1. A typical STRB system.

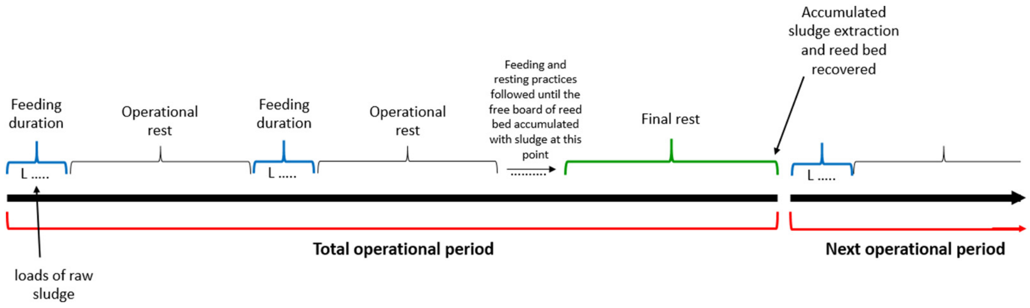


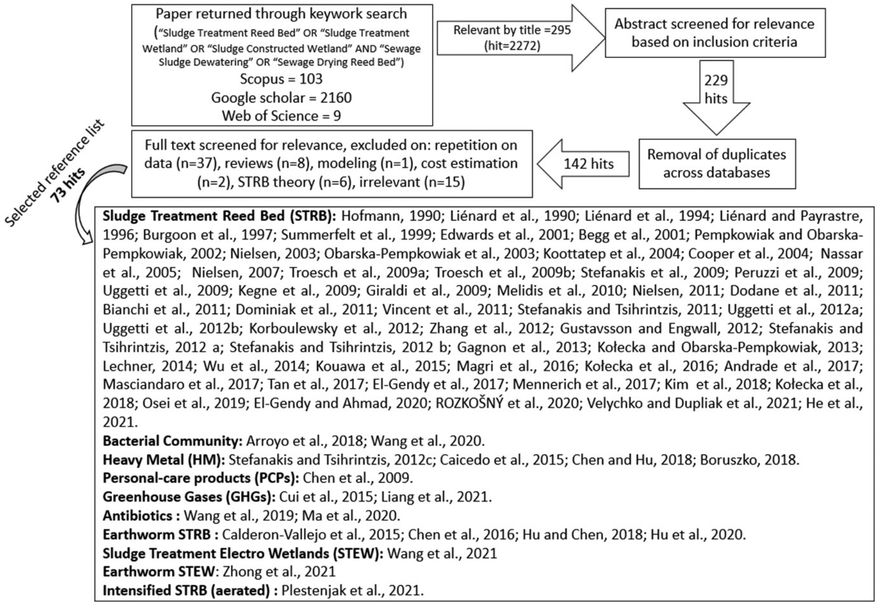
Fig. 2. Schematic representation of STRB operation periods.

content, and extract residual sludge (Pandey and Jenssen, 2015). Practically, after the extraction of accumulated sludge, the reed bed is ready for the next phase of operation. STRB can be utilized for almost 10 or 15 years depending on the height of the freeboard considered (usually between 0.5 and 1.5 m) and other criteria including the climate condition and the volume of the accumulated sludge determine STRB lifespan (Nielsen and Larsen, 2016; Brix, 2017). By desludging the process, the system can be simply recovered from the first lifespan and operated for the next lifespan (Nielsen, 2007).

2.2. Data collection and characterization

The data for Meta-Analysis (MA) was collected from Google Scholar, Scopus, and Web of Science (only English documents were considered) (Schulze, 2004; Field and Gillett, 2010; Hedges and Olkin, 2014). The search was performed through several combinations of keywords as one of the inclusion criteria: “Sludge Treatment Reed Bed” OR “Sludge Treatment Wetland” OR “Sludge Constructed Wetland” AND “Sewage Sludge Dewatering” OR “Sewage Drying Reed Bed.” The search returned 2272 hits including 2160, 103, and 9 hits from Google Scholar, Scopus, and Web of Science, respectively. To either reject or select the hits, inclusion, and exclusion criteria were applied in the meta-analysis of this review (Lozanovska et al., 2018; Kumar et al., 2019; Niu et al., 2020). Inclusion criteria were hits with Sludge Treatment Reed Bed title and content, hits applied to pilot and/or full scale, and hits with English texts. In addition, it is important to highlight that only the studies that presented the result in STRB experiments were taken into consideration to allow for homogeneity in the same database. Second, they should include the following information, including design, operation, and performance criteria. The exclusion criteria are those STRB hits that provided neither the operational parameters nor dewatering performance of STRBs including SLR, DS, VS, and resting periods, STRB hits that have data repetitions and duplication in different databases and journals, STRB hits with reviews and viewpoints, STRB hits with modeling and simulation content, STRB hits with cost assessment purposes, STRB hits with general concepts and theoretical hits. A total of 295 articles were detected within the scope of the study via title checking. Afterward, 66 irrelevant articles were removed through relevance based on inclusion criteria by abstract screening. Therefore, 229 articles remained of which 78 were duplicated through databases, and the remaining 142 papers were selected for full-text reading. Finally, 69 articles were excluded based on exclusion criteria including data publishing repetition ($n = 37$), reviews ($n = 8$), modeling ($n = 1$), cost estimation ($n = 2$), STRB theory ($n = 6$) and irrelevant data to STRB ($n = 15$). Therefore, 73 original papers were selected and 66 studies of typical STRB were considered for the Meta-Analysis (MA) from 1990 until 2021 (30 years of relevant studies). Seven studies had modified designs including earthworm STRB, Sludge Treatment Electro Wetland (STEW), earthworm STEW, and aerated STRB (intensified) were used in this review to draw a comparison with typical STRB studies. Although the excluded articles did not have relevant data for the MA of the STRB design factors, they are often referred to within the review for their scientific findings and contributions to a specific thematic. The process of the search and data collection is shown in Fig. 3.

The selected references can be seen in Fig. 3, categorized into different topics based on the purpose of the investigations, and the differences in reed bed design. Of the studies, 66 cases were on the typical STRB



Sludge Treatment Reed Bed (STRB): Hofmann, 1990; Liénard et al., 1990; Liénard et al., 1994; Liénard and Payrastre, 1996; Burgoon et al., 1997; Summerfelt et al., 1999; Edwards et al., 2001; Begg et al., 2001; Pempkowiak and Obarska-Pempkowiak, 2002; Nielsen, 2003; Obarska-Pempkowiak et al., 2003; Koottatep et al., 2004; Cooper et al., 2004; Nassar et al., 2005; Nielsen, 2007; Troesch et al., 2009a; Troesch et al., 2009b; Stefanakis et al., 2009; Peruzzi et al., 2009; Uggetti et al., 2009; Kegne et al., 2009; Giraldi et al., 2009; Melidis et al., 2010; Nielsen, 2011; Dodane et al., 2011; Bianchi et al., 2011; Dominiak et al., 2011; Vincent et al., 2011; Stefanakis and Tsihrintzis, 2011; Uggetti et al., 2012a; Uggetti et al., 2012b; Korboulewsky et al., 2012; Zhang et al., 2012; Gustavsson and Engwall, 2012; Stefanakis and Tsihrintzis, 2012 a; Stefanakis and Tsihrintzis, 2012 b; Gagnon et al., 2013; Kołecka and Obarska-Pempkowiak, 2013; Lechner, 2014; Wu et al., 2014; Kouawa et al., 2015; Magri et al., 2016; Kołecka et al., 2016; Andrade et al., 2017; Masciandaro et al., 2017; Tan et al., 2017; El-Gendy et al., 2017; Mennerich et al., 2017; Kim et al., 2018; Kołecka et al., 2018; Osei et al., 2019; El-Gendy and Ahmad, 2020; ROZKOŠNÝ et al., 2020; Velychko and Dupliak et al., 2021; He et al., 2021.
Bacterial Community: Arroyo et al., 2018; Wang et al., 2020.
Heavy Metal (HM): Stefanakis and Tsihrintzis, 2012c; Caicedo et al., 2015; Chen and Hu, 2018; Boruszko, 2018.
Personal-care products (PCPs): Chen et al., 2009.
Greenhouse Gases (GHGs): Cui et al., 2015; Liang et al., 2021.
Antibiotics : Wang et al., 2019; Ma et al., 2020.
Earthworm STRB : Calderon-Vallejo et al., 2015; Chen et al., 2016; Hu and Chen, 2018; Hu et al., 2020.
Sludge Treatment Electro Wetlands (STEW): Wang et al., 2021
Earthworm STEW: Zhong et al., 2021
Intensified STRB (aerated) : Plestenjak et al., 2021.

Fig. 3. The process of web search and data collection.

performances, the operational adaption to a certain climate, and the type of raw sludge, of which there are two studies on bacterial communities, four on Heavy Metals (HMs), one for Personal-Care Products (PCPs), two for Greenhouse Gases (GHGs), two for Antibiotics, four for Earthworm STRB, one for Sludge Treatment Electro Wetlands (STEWs), one for Earthworm STEW and one for Intensified STRB (aerated STRB). Based on the structural development over 30 years, STRB technology has been designed in four different classifications including STRB, Earthworm STRB, STEW, and Earthworm STEW. The addition of Earthworm (Calderón-Vallejo et al., 2015; Chen et al., 2016; Hu and Chen, 2018; Hu et al., 2020), power generation (Wang et al., 2021), synchronous earthworm, and power generation (Zhong et al., 2021) and active aeration (Plestenjak et al., 2021) can be considered the state of the art of the technology. The addition of earthworms can accelerate the dewatering and stabilization processes due to the movement of earthworms together with the direct consumption of organic matter (Chen et al., 2016). The introduction of the microbial electrochemical system (MES) was conducted to enhance the conventional STRB efficiency and to generate power out of organic matters (Wang et al., 2021). Zhong et al. (2021) have combined two systems of earthworm STRB and STEW and created earthworm STEW that enabled to generate power and enhanced the dewatering and stabilization efficiencies of the typical STRB. A typical STRB has been designed with passive aeration tubes that passively supply air to the reed bed to enhance the process of organic matter decomposition. Another important development was the introduction of active (forced) aeration in STRB media by using a blower (Plestenjak et al., 2021).

A statistical analysis of the number of publications by the continent, country, and journal of publication was performed, and the result is shown in Fig. 4.

Based on the world map (Fig. 4), most investigations were in Europe and Asia, particularly in China with 16 publications. In Europe, there were 14 studies in Denmark and eight in France along with eight investigations in Poland. Although there have been three and four studies in South and North America, respectively, only three studies have been reported from Africa.

We conducted a terminological analysis on the keywords that have been used frequently in previous studies. Through the Meta-analysis, it is found that different terminologies were used to state STRB technology in the literature, which brings difficulty for the research tools to provide relevant studies. The terminology analysis contributes to the identification of common and most widespread terms used in previous studies to harmonize future studies in the application of such keywords. In the analysis, all keywords of the selected studies were collected, and the frequency of each keyword was determined. It showed that keywords like "reed bed", "dewatering", "sludge treatment wetland", "sludge dewatering", "constructed wetland" and "sludge" have been repeated 21, 17, 14, 12, 11, and 11 times, respectively. Other keywords including "sewage sludge", "*Phragmites australis*", "bio-solids", "sludge Treatment Reed Beds", "sludge drying", "sludge drying bed", "nutrient" and "heavy metals" were also used between five and ten times.

From 1990 to 2021, different milestones in the sludge dewatering science can be identified through reed beds or constructed wetlands. The milestones are defined as whether the technology was used for the first time in a region or a country and in case any variation happened in the technology design or the investigated objectives. Fig. 5 shows a timeline of the technology since 1990 and the relevant milestones.

In 1990, the first STRB studies were conducted in Germany and France followed by a study in 1996, in France, where a reed bed was used for the dewatering of septic tank raw sludge (Hofmann, 1990; Lienard et al., 1990; Liénard and Payrastre, 1996). In 1997, an application of STRB was reported for the first time in the USA (Burgoon et al., 1997) and the experiences of Polish STRB's stated in 2000 (Zwara and Obarska-Pempkowiak, 2000). In Asia, the first STRB study was performed in Thailand (East Asia, in 2004) followed by a study in 2005, in Palestine, West Asia (Koottatep et al., 2005; Nassar et al., 2006). In 2009, the objective of the studies developed in Germany was to explore the fate of PCPs in accumulated sludge, which is a more specific subject (Chen et al., 2009). The first regional review of the STRB was reported in 2010, in Spain, in which the technology was defined and there was a discussion over the overall performance of

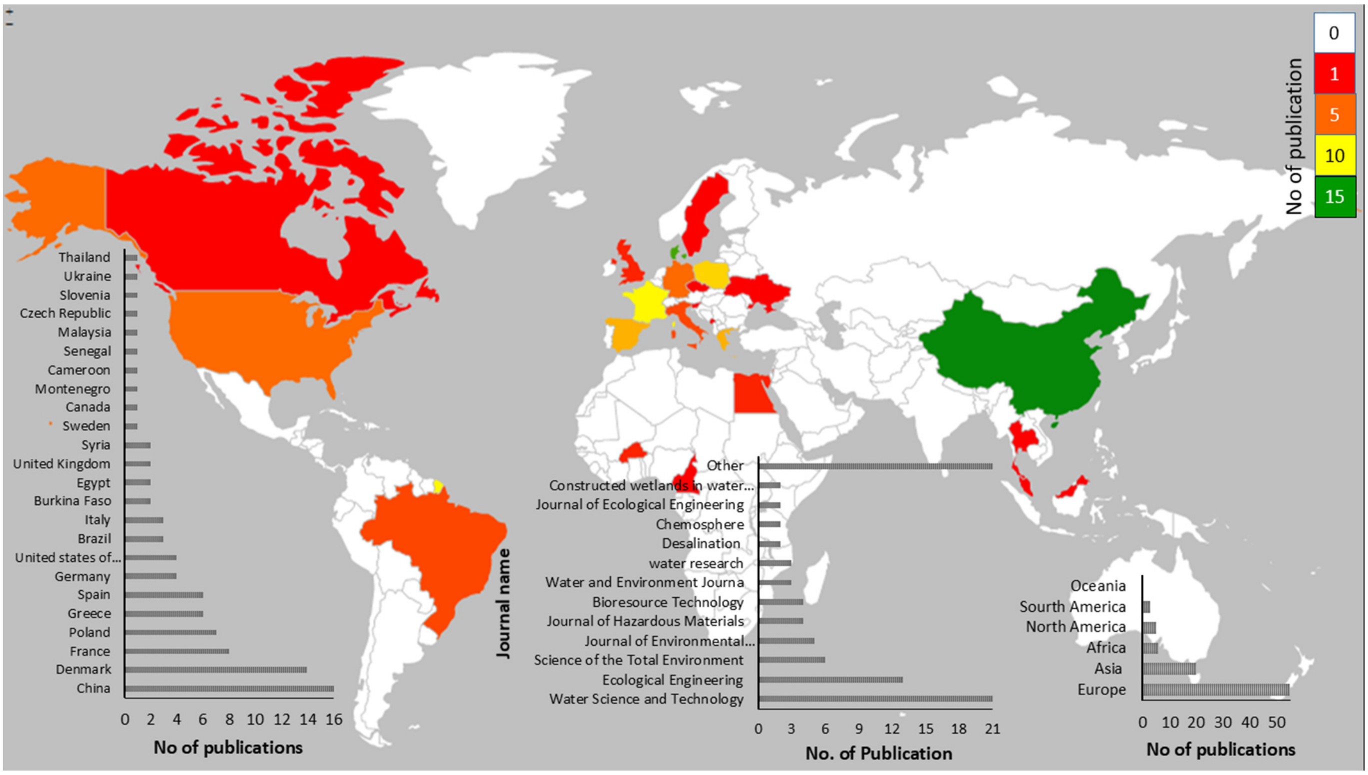


Fig. 4. Location of the selected studies and journal of publication.

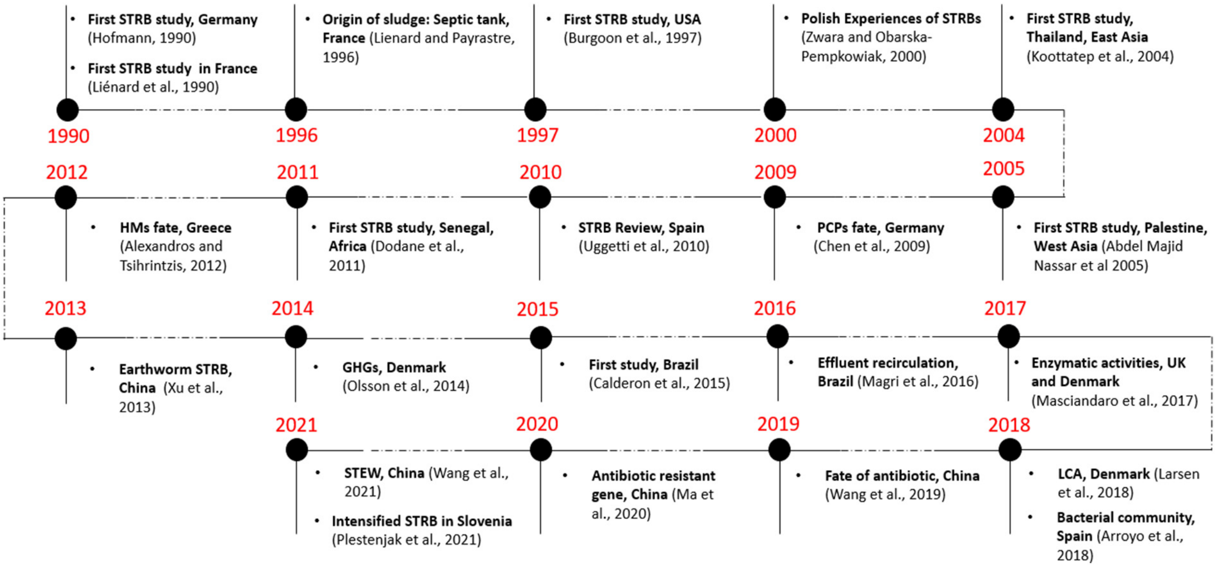


Fig. 5. STRB timeline and milestones since 1990.

STRB (Uggetti et al., 2010). In 2011, the first study of STRB in Africa, Senegal, was documented (Dodane et al., 2011). The fate of heavy metals in accumulated sludge and drainage water quality was investigated in 2012 (Stefanakis and Tsihrintzis, 2012b), and afterward, the STRB system was used together with earthworms in 2013, in China (Xu et al., 2013). The amount of GHGs emitted from STRB was reported in Denmark in 2014 (Olsson et al., 2014). The first study of STRB, which was applied to earthworms as well, was conducted in Brazil, South America in 2015 (Calderón-Vallejo et al., 2015). Magri et al., investigated for the first time the effect of effluent recirculation on STRB in 2016 (Magri et al., 2016), and then the enzymatic activities were explored in UK and Denmark in 2017 (Masciandaro et al., 2017). In 2018, there were two studies on Life Cycle Assessment (LCA) and bacterial communities in Denmark and Spain respectively (Nielsen and Larsen, 2016; Arroyo et al., 2018). The fate of antibiotics and Antibiotics Resistant Genes (ARGs) were studied in China in 2019 and 2020 (Wang et al., 2019; Ma et al., 2020). In 2021, studies of STEW and Intensified STRB were reported as well (Wang et al., 2021; Plestenjak et al., 2021).

2.3. Data analysis

To find a significant difference between climate conditions (p-value < 0.05), Analysis of Variance (ANOVA) was conducted using statistical tools e.g., R between STRB parameters of operation and efficiency. Normality of data was assessed via the Shapiro-Wilk test and homogeneity of variance (Levene's test) was performed ($p > 0.05$). Other statistics such as min, max, mean, standard deviation, and analysis of the level of confidence (upper and lower limits with 95 % level of confidence) were calculated as well.

Statistical package R was used to conduct all analyses. The operational parameters of STRB considered in the analysis included Sludge Loading Rate (SLR), feeding and resting modes, Dry Solids (DS) and Volatile Solids (VS) obtained from the accumulated sludge, height of the accumulated sludge, and the sludge volume reduced during feeding and after final resting. It has been suggested that climate condition is the most effective criterion influencing the overall performance of STRB technology and the design aspects (Kengne and Tilley, 2014; Gholipour et al., 2015; Nielsen and Larsen, 2016).

In this study, Köppen–Geiger climate classification system is used (Beck et al., 2018), which suggests mainly four climate conditions including Temperate, Tropical, Arid, and Polar. Solar radiation across the Temperate climate varies from relatively high radiation in the Mediterranean region (1700 kW/m^2) to a lower intensity (1200 kW/m^2) in Western, Eastern, British Isles, and Northern Europe regions (Paulescu et al., 2013; Dash et al., 2017; Anas et al., 2021). Solar radiation has been correlated with the evapotranspiration rate (Chatzithomas and Alexandris, 2015; Mokhtari et al., 2018), which was found an effective factor in the dewatering process of sludge in a system of an STRB (Brix, 2017). In this study, Temperate climate was divided into the Temperate type 1 (relatively low-intensity solar radiation) and Temperate type 2 (relatively high-intensity solar radiation). As the solar radiation of the Temperate type 1 and Temperate type 2 is different, we hypothesized that there would be a significant difference between the type 1 and 2 in terms of the operational, design factors, and efficiency factors. Therefore, the hypothesis is assessed in this study to present a more relevant meta-analysis for this region. Temperate type 1 refers to the region with lower intensity of solar radiation which is categorized as humid subtropical (Cfa), oceanic (Cfb), subpolar oceanic (Cfc), dry-winter humid subtropical (Cwa), dry-winter subtropical highland (Cwb), and dry-winter cold subtropical highland climate (Cwc). Temperate type 2 is the region with higher intensity of solar radiation, which refers to a hot and warm (Csa, Csb, and Csc).

Since there is not sufficient data on the latest advances such as earthworm STRB, STEW, earthworm STEW, and intensified STRB to conduct statistical analysis, only the studies of typical STRBs were considered in MA. The results of the climatic categories of the STRB analysis will be later compared with the latest advances though. It contributes to clarifying if there is any enhancement of the STRB technology through the variations in the different types of the latest designs.

3. Results and discussion

Our analysis showed that 64 % of the studies were pilot scales while 36 % were full scales. 90 % of the cases were about domestic sludge (WWTPs, pit latrine, or septic tanks) followed by 4 % for industrial sludge, and few studies explored the efficiency of STRB for the fishery, aquaculture, and livestock sludge sources (Summerfelt et al., 1999; Gagnon et al., 2013; Arroyo et al., 2018). In the studies on WWTP sludge, 60 % of the sludge fed was a combination of primary and secondary sludge (mixed sludge) and 32 % was primary sludge while only 8 % was secondary sludge. In terms of the origin and the technology of the treatment, the data showed that 51 % of the sludge was Surplus Activated Sludge (SAS) followed by 24 % from pit latrine and septic tanks. Some studies investigated the sludge from extended aeration systems (12 %) while other studies included anaerobic sludge, Imhoff tanks, reflux tanks, trout production, swine slurry, and settled fish farm sludge were conducted (Summerfelt et al., 1999; Melidis et al., 2010; Magri et al., 2016; Arroyo et al., 2018; Rozkošný et al., 2020;

Wang et al., 2021). Of the total 74 selected studies, 66 cases had an STRB area of <5000 m^2, and the remaining cases were performed in an area larger than 5000 m^2. In terms of studies' duration, 12 studies were less than one year, and 38 studies had a duration length between one and five years. Only 13 cases were reported having more than a five-year operational period. It is also found that the average Dry Solid (DS) and Volatile Solid to DS (VS/DS) of the raw sludge were 6.64 and 64 % in the previous studies, respectively. More information on the 73 selected studies can be found in the Supplementary materials (Appendix 1).

3.1. Design and operational aspects

Three parameters in the operation of STRB affect the final performance of a dewatering process, which include Sludge Loading Rate (SLR), mode of sludge feeding, and resting period (Nielsen, 2005). The factors were analyzed for five different climate conditions including a total of 76 STRB facilities from Temperate type 1 (35), Temperate type 2 (15), Tropical (19), Arid (3), and Polar (1) climates. Fig. 6 presents the statistical analysis of SLR for different climate conditions. For each climate, the maximum and minimum values are presented as well as the upper and lower limits for SLR, which was considered the 95 % confidence level. The homogeneity of variance for the data collected was found equal (p-value > 0.05) and, the data were normally distributed (p-value > 0.05). The average SLR values of Temperate type 1, Temperate type 2, and Tropical climates increased with the reduction of latitude with the SLRs values of 50, 70, and 101 Kg.DM.m^{-2}.year^{-1}, respectively. These values were found to be statistically significantly different (p-value < 0.05).

In a Temperate type 1, the upper and lower limits of application were 59.49 and 41.42 Kg.DM.m^{-2}.year^{-1}. In the Temperate type 2, the upper and lower limits of application were 91.21 and 48.88, and for Tropical climates are 130.39 and 71.5 Kg.DM.m^{-2}.year^{-1}, respectively. The reported values of Arid and Polar climates are 80 and 30 Kg.DM.m^{-2}.year^{-1} in Senegal and Canada, respectively (Dodane et al., 2011; Gagnon et al., 2013). Based on this, the highest numbers of SLR occurred in the lower geographical latitudes, which correspond to the warmer climates with fewer days of precipitation. (Although we compare the average values of the meta-analysis, the upper and lower limits of each climate can be used to compare climate more precisely distinction).

Earthworm STRB studies from the Tropical region (four studies) showed that SLR can be applied up to 120 Kg.DM.m^{-2}.year^{-1} (Calderón-Vallejo et al., 2015; Chen et al., 2016; Hu and Chen, 2018; Hu et al., 2020) while the average SLR for typical STRBs is 101 Kg.DM.m^{-2}.year^{-1}. The SLRs adapted in the systems of STRB assisted with earthworms are within the range of upper and lower limits for typical STRB in Tropical climates; therefore, the average SLR adapted for Earthworm STRB shows an improvement compared to the typical STRBs. SLRs for STEW and earthworm STEW in Tropical climates were 125 and 91.2 Kg.DM.m^{-2}.year^{-1}, respectively (Wang et al., 2021; Zhong et al., 2021). The SLR adapted for intensified STRB in Slovenia was 21.5 Kg.DM.m^{-2}.year^{-1} (Plestenjak et al., 2021). Thus, a system of STEW could dewater the maximum amount of fed sludge within all STRB types in the Tropical region. Due to data insufficiency, a similar comparison for other climates is not addressed.

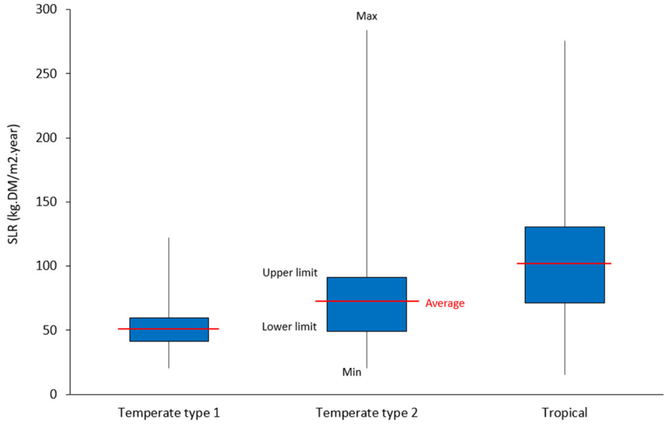


Fig. 6. Statistical analysis of SLR for the three different climate conditions.

The operation of STRB was analyzed considering the feeding duration, and operational stages including operational rest, and final rest (Fig. 7). The distribution of data in each climate was found normal, and the homogeneity of variance was met as well (P-value > 0.05). ANOVA analysis showed that the data obtained for Temperate type 1, Temperate type 2, and Tropical climates are significantly different (p-value < 0.05).

According to Fig. 7(a), the average feeding durations are 6.44, 3.26 and 2.23 days for Temperate type 1, Temperate type 2, and Tropical climate conditions, sequentially. In addition, average operational rests were 22, 17, 11, and 7 days for Temperate type 1, Temperate type 2, Tropical, and Arid climate conditions, respectively (Fig. 7.b).

Several factors including precipitation, the season of the final resting, solar radiation, humidity, wind, and evapotranspiration influence the duration of the final resting (De Maeseneer, 1997; Brix, 2017). Higher precipitation during the final resting period increases the duration of the final resting (Kengne and Tilley, 2014). In Temperate climate type 1, the final resting duration ranged from 24 days in Germany (Hofmann, 1990) to 365 days in France and in Montenegro (Vincent et al., 2011; Lechner, 2014). In France, Liénard et al. (1995) also applied 70 days and in the UK, 120 days were also considered by Edwards et al. (2001). In Denmark, Uggetti et al. (2012b) and Masciandaro et al. (2017) applied 90 and 60 days, respectively, while in Helsinge facility in Denmark, the duration was 14 months (from June 2004 to August 2005) (Nielsen, 2007). In Temperate climate type 2, the duration of the final resting varies from 25 (in Greece, Stefanakis and Tsihrintzis, 2011) to 180 days (in Egypt, El-Gendy and Ahmedb, 2020). In Spain, 90 days were applied by Uggetti et al. (2012a) and Arroyo et al. (2018). In the Tropical climate, the final resting was 30 days in Cameron (Kengne et al., 2009), and in China, the final resting ranged from 30 to 365 days while most studies in China considered 365 days (Zhang et al., 2012; Cui et al., 2015; Chen and Hu, 2019; Wang et al., 2019; Ma et al., 2020; Wang et al., 2020; He et al., 2021; Liang et al., 2021; Zhong et al., 2021). Through the previous studies, there has not been any design guideline on the duration of the final resting; however, the final resting duration depends on the desired degree of final DS and the application of the final dried solid (Brix, 2017). The occurrence of the final resting was recommended in seasons with lower precipitations (Nielsen, 2005).

During feeding, the selected SLR can be fed over the reed bed in one or more loads (Brix, 2017). In the Temperate type 1, Summerfelt et al. (1999) within a one-day feeding, fed the reed bed in six loads while in the facility of Rudkøbing in Denmark, it is reported that one load was considered for a one-day feeding (Nielsen, 2003). Wu (2014) also considered two loads in 3.5 days of feeding duration in a Temperate type 1 while Rozkošný et al. (2020) perceived two different modes of loading and feeding I) four loads of raw sludge in 90 days II) 15 loads of raw sludge in 25 days of feeding duration. In the Temperate type 2, one week of daily loading and 7, 14 and 21 days of operational rest were considered by Stefanakis et al. (2009) while Uggetti et al. (2009) had 12 loads during two days of feeding in Alpens and Sant Boi facilities. In addition, one load during a one-day feeding was perceived by Arroyo et al. (2018) in the Temperate type 2. In the Tropical climate, Calderón-Vallejo et al. (2015) fed the pilot reed bed with eight loads in one day while Wang et al. (2021) considered five loads in five days of feeding duration. One load was taken into consideration in a one-day feeding by Kouawa et al. (2015) while Osei et al. (2019) fed the reed bed with two loads in a one-day feeding in an Arid climate condition. In the Polar climate, one load was considered in a one-day feeding by Gagnon et al. (2013).

Our analysis showed that the feeding and resting periods of earthworm STRB (1 to 2 days feeding and 7 to 14 days resting), STEW (5 days feeding and 4 days resting), earthworm STEW (4 days feeding and 4 days resting), intensified STRB (1 day feeding and 40 days resting) have been quite like the typical STRB studies. Table 1 presents a summary of the meta-analysis on the design and operational aspects of typical STRB.

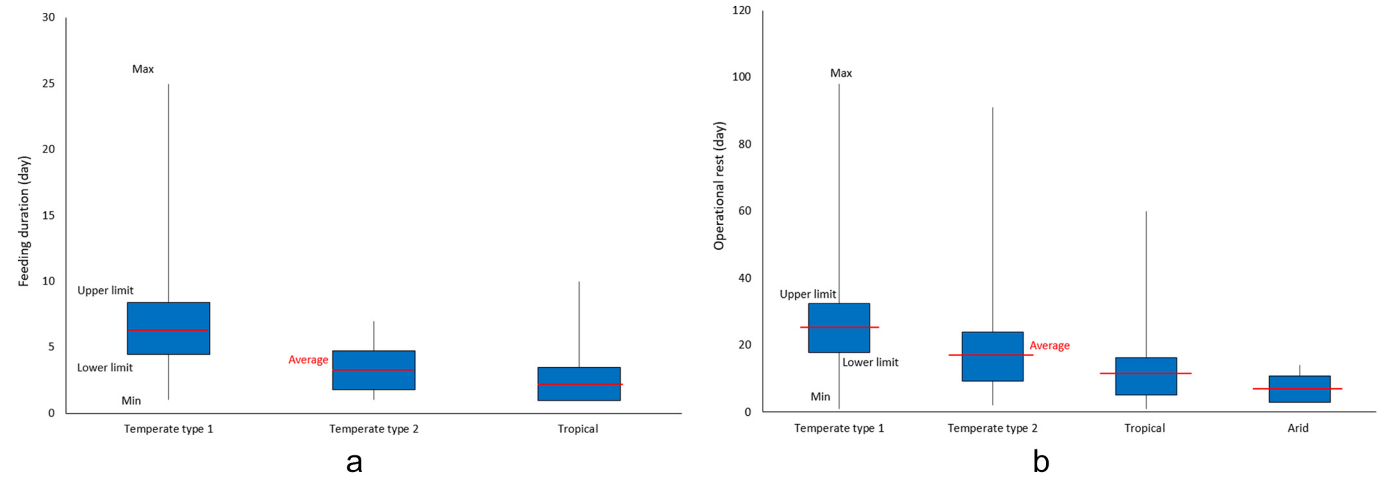


Fig. 7. Statistical analysis: a) feeding duration b) operational rest (data is shown only for climates with 3 or more studies).

3.2. Performance

The performance of an STRB system in terms of the dewatering process is measured based on dry and volatile solids obtained either during or after resting (Brix, 2017). Several criteria are used to determine the performance of a reed bed including Dry Solids (DS) content of the accumulated sludge, the proportion of Volatile Solids (VS) to Dry Solids (VS/DS), the thickness of the residual sludge (height of accumulated sludge) and the percentage of sludge volume reduced (Nielsen and Larsen, 2016). The present study conducted a statistical analysis of the DS content, VS/DS, the final sludge thickness, and the reduced volume of sludge and categorized them into different climate conditions. Fig. 8 shows the DS content of the accumulated sludge (Fig. 8.a and b) and the VS/DS (Fig. 8.c and d) during feeding and after final resting. The homogeneity of variance and normal distribution of the data was met (p-value > 0.05) and ANOVA analysis showed that the data obtained from different climates are significantly different (p-value < 0.05).

Previous studies showed that the DS during the feeding is always less than the DS obtained after the final resting (Peruzzi et al., 2009; Giraldi et al., 2009; Osei et al., 2019). According to Fig. 8.a, the average DS during the feeding for Temperate type 1, Temperate type 2, and Tropical climates are 33, 35, and 40 %, respectively. Dodane and Gagnon's studies showed that 45 and 30 % of DS can be obtained in Arid and Polar climates (Dodane et al., 2011; Gagnon et al., 2013). The average DS content of sludge after the final rest is 45 % for Temperate type 1 (Fig. 8.b), and in Temperate type 2, 80.5 % was obtained (Stefanakis and Tsihrintzis, 2012b). The study by Wang et al. (2020) revealed that DS content after final resting can reach 59 % in an STRB system in Tropical climates.

The average DS obtained from earthworm STRBs in Tropical climate after final resting was 63.4 % which is higher than that of 59 % for the typical STRBs in the Tropical region while this value was 11.5 and 50 % for the systems of STEW and earthworm STEW (Calderón-Vallejo et al., 2015; Chen et al., 2016; Hu and Chen, 2018; Hu et al., 2020; Wang et al., 2021; Zhong et al., 2021). A final DS of 62.5 % was reported for the intensified STRB (Plestenjak et al., 2021). Therefore, the dewatering performance of earthworm STRBs can potentially be higher than that of typical STRBs in Tropical regions. In a Temperate type 1, the final DS of intensified STRB is higher than that of typical STRB reported in Plestenjak et al. (2021)

Table 1
A summary of meta-analysis on design and operational aspects of STRB.

Parameters type	Parameters	Statistics	Unit	Climate condition				
				Temperate type 1	Temperate type 2	Tropical	Arid	Polar
Design and operational aspects	Sludge Loading Rate (SLR)	Min	kg.DM/m^2.year	20	20	15		
		Max		122	284	276		
		Mean		50	70	101	[a]	[a]
		Lower limit		41.42	48.88	71.5		
		Upper limit		59.49	91.21	130.39		
		No of studies	Number	28	23	25		
	Number of loads	Min	Number	1	1	1	1	
		Max		15	12	8	2	
		Mean		2.18	2	1.73	1.25	
		Lower limit		0.87	0.21	0.71	0.76	[a]
		Upper limit		3.48	3.78	2.75	1.74	
		No of studies		22	12	15	4	
	Feeding duration	Min	Day	1	1	1		
		Max		25	7	10		
		Mean		6.44	3.26	2.23		
		Lower limit		4.45	1.79	0.99	[a]	[a]
		Upper limit		8.43	4.74	3.47		
		No of studies	Number	27	13	20		
	Operational rest	Min	Day	1	2	1	3	
		Max		98	91	60	14	
		Mean		22	17	11	7	[a]
		Lower limit		17.75	9.16	5.16	2.86	
		Upper limit		32.55	24.01	16.26	10.73	
		No of studies	Number	35	22	20	7	

[a] Less than 3 studies.

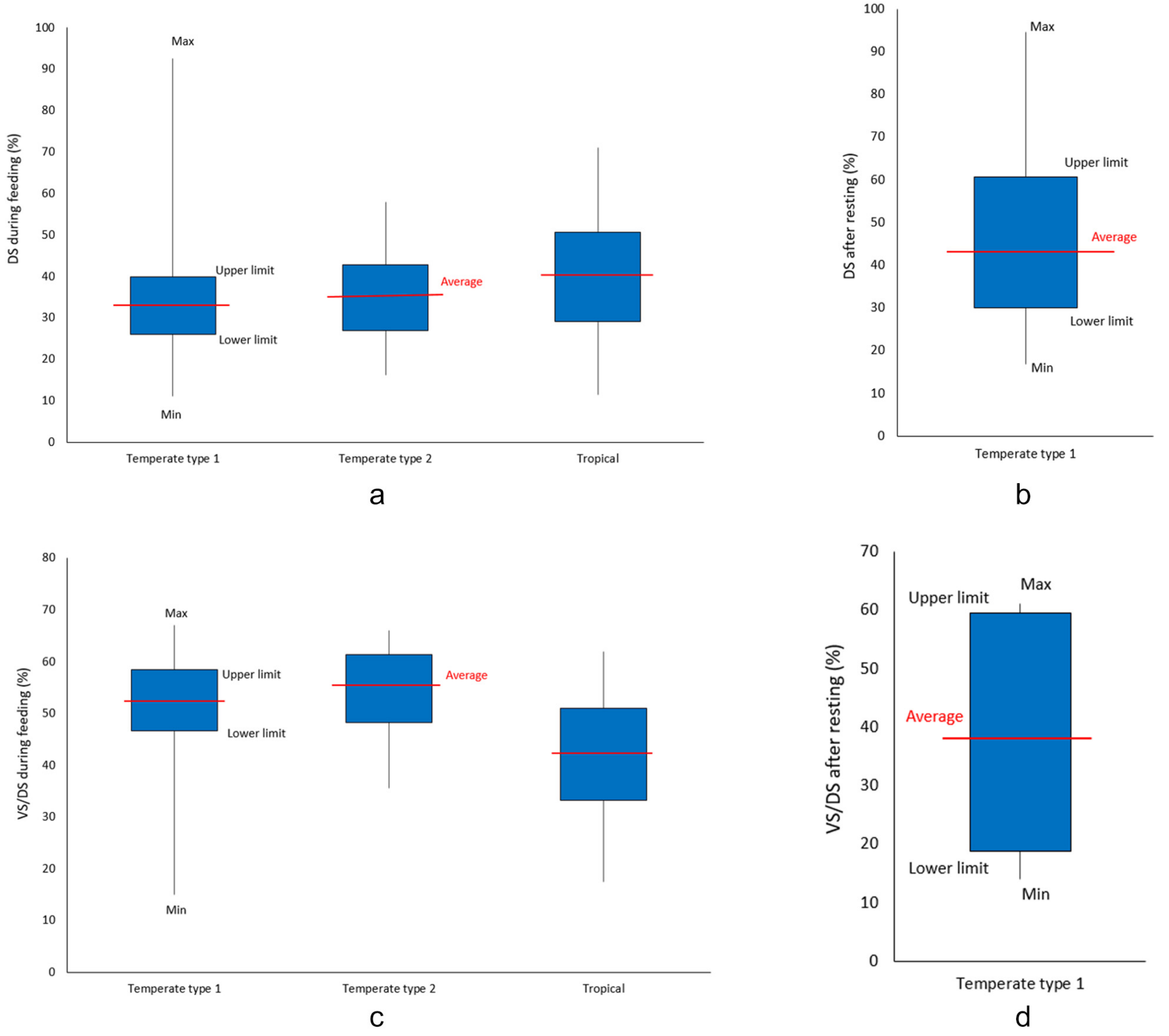


Fig. 8. Statistical analysis: a) DS during feeding b) DS after final resting c) VS/DS during feeding d) VS/DS after final resting (data is shown only for climates with 3 or more studies).

study. The reason for this could be the lower SLR applied on the intensified STRB (21.5 Kg.DM.m^{-2}.year^{-1}) while the average SLR for typical STRBs in Temperate type 1 was 50 Kg.DM.m^{-2}.year^{-1}. Overall, the final DS obtained in the Temperate type 2 climate was 70 %, which is the highest DS of all climates for the typical STRBs and even compared to the latest advances of STRB. Although it is evinced that higher SLRs are adopted in the lower geographical latitudes and warmer climates (Fig. 6), the highest DS resulted from MA in Fig. 8 between higher and lower latitudes. Apart from SLR applied, other factors influence the final DS after the final resting including precipitation, wind speed, solar radiation, evapotranspiration, humidity, and seasonal effects (Nielsen, 2007; Arroyo et al., 2018). A Higher DS in the Temperate type 2 climate could be due to the aforementioned factors.

The ratio of VS to DS is a key criterion for showing the amount of decomposable sludge (Brix, 2017). According to Fig. 8.c, the studies under Temperate type 1, Temperate type 2, and Tropical climates give average values of VS/DS (during feeding) of 53, 55, and 42 %, respectively, and for Polar climate, this number is 40 % (Gagnon et al., 2013). After the final resting, the average VS/DS is 39 in Temperate type 1 (Fig. 8.d), and for Temperate type 2 was reported 67.4 % (Stefanakis et al., 2009) while 52 % was obtained in Tropical climate by Cui et al. (2015). The difference between the average VS/DS values in Temperate type 1 climates during feeding (53 %) and after final resting (39 %) can be due to several reasons, like precipitations and the different periods during the feeding and the final resting. Although the final average VS/DS of Temperate type 1 is lower than that of the average value during the feeding period, the range of upper and lower limits of Temperate type 1 after resting (Fig. 8.d) is larger than the range of upper and lower limits during the feeding in Temperate type 1 (Fig. 8.c), where the upper limits of both ranges are 59.5 and 58.42 %, respectively. The reasons for the difference in Temperate climate should be addressed in future research.

The VS/DS of the studies for the earthworm STRB, STEW, and earthworm STEW in Tropical climates were reported at 33.1, 33.6 and 41.6 %, respectively (Calderón-Vallejo et al., 2015; Chen et al., 2016; Hu and Chen, 2018; Hu et al., 2020; Wang et al., 2021; Zhong et al., 2021). Hence, VS/DS values of these systems are lower than the typical STRBs values, indicating improved stabilization efficiency. The amount of sludge accumulated per year and the sludge volume reduced are also important criteria, which directly influence the size of reed bed, excavation, and transportation costs of sludge for further land applications (Nielsen, 2005). The increment of sludge height per year for each climate condition and the amount of sludge reduced after final resting is shown in Fig. 9. The

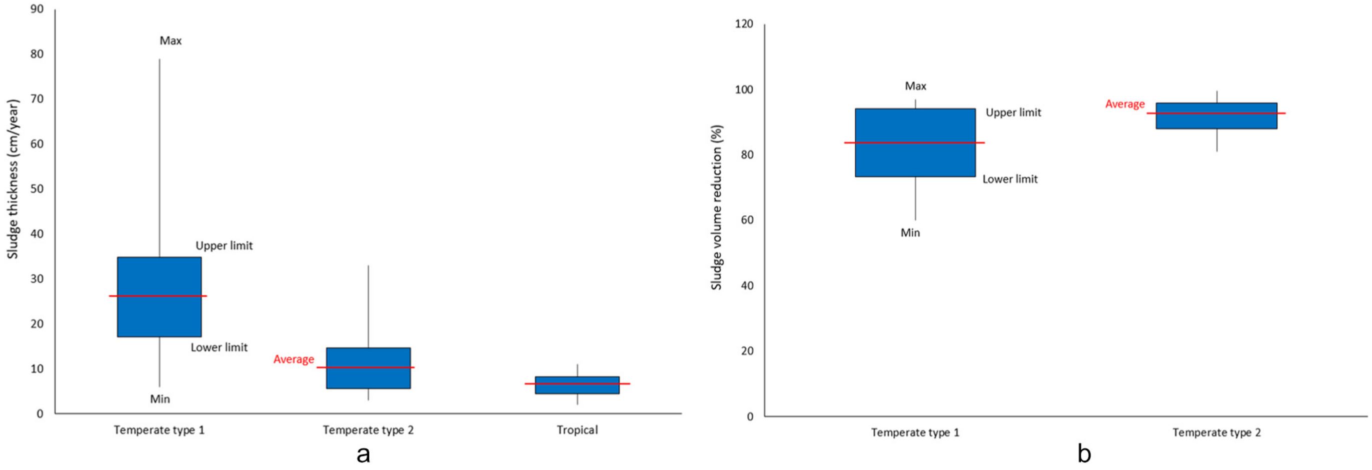


Fig. 9. Statistical analysis: a) sludge thickness b) volume reduced (data is shown only for climates with 3 or more studies).

distribution of the data was normal, and the variances were homogeneous (*p*-value > 0.05). ANOVA analysis indicated that the data obtained from different climates are significantly different (p-value < 0.05).

Evapotranspiration (ET) is an effective factor influencing the final DS of sludge (Burgoon et al., 1997; Velychko and Dupliak, 2021). The type of plant species, seasonal effect, climate conditions, atmosphere humidity, wind speed, and the presence of earthworms in the STRB system were found effective on the rate of ET (Burgoon et al., 1997; Vincent et al., 2011; Stefanakis and Tsihrintzis, 2011; Chen et al., 2016; Mennerich et al., 2017; Hu and Chen, 2018; Velychko and Dupliak, 2021). It is stated that during the growing season, the rate of ET is higher and from April to September is 1.9 mm per day while it can range from 1.23 to 1.78 mm per day in a Temperate type 1 (Velychko and Dupliak, 2021). A study by Burgoon et al. (1997) showed that ET could be 6.4 mm per day between May to Jun in a Temperate type 1 while the ET rate in the study by Vincent et al. (2011) also in a Temperate type 1 reported 2.58 mm per day, resulting in 70 % of DS. Other studies found that the ET rate can range from a minimum of 1.34 mm to a maximum of 1.90 mm per day in a Temperate type 1 in which the DS ranged between 20 and 45 % (Mennerich et al., 2017). Therefore, the DS obtained in the study of Vincent et al. (2011) is higher than that of the DS obtained by Mennerich et al., in the Temperate type 1 due to a higher rate of ET. A significant difference in the rate of ET was observed between different plant species in which *Phragmites australis*, *Typha angustifolia*, and *Scirpus fluviatilis* show 94, 64, and 40 % of ET, respectively (Gagnon et al., 2013). Earthworm STRB system showed a higher ET rate compared to typical STRBs by a 42.9 % increase in ET (Chen et al., 2016). This could be since earthworms increase the exchange of water in the STRB system with the atmosphere and then, ET increases while draining can also be enhanced by earthworms creating micro tunnels in the reed bed media. This increases the final DS content of the sludge accumulated as well (Hu and Chen, 2018).

In Fig. 9.a, the height of the average sludge accumulated annually is 26, 10, and 6 cm for Temperate type 1, Temperate type 2, and Tropical climates, respectively. This number is reported as 30 cm per year for the Arid climate (Dodane et al., 2011). Therefore, the lowest value of accumulated sludge occurs in Tropical climates at 6 cm per year. The average sludge volume reduced was 84 and 92 % for Temperate type 1 and Temperate type 2 climates (Fig. 9.b). In Tropical and Polar regions, volume reduction was averagely reported as 98.55 and 86.5 % (Chen et al., 2016; Gagnon et al., 2013).

In comparison to the earthworm STRB, STEW, and earthworm STEW, the height of accumulated sludge is much lower than the typical STRBs, which have been reported as 2 cm per year. Therefore, a system of combined earthworms and typical STRB or MES, or STEW can reduce the amount of sludge accumulated more efficiently (>60 %). Synchronous earthworms or MES with STRB can enhance the general performance and removal efficiency resulting in less accumulated sludge in reed beds due to the possibility of a higher decomposition rate. Table 2 presents a summary of MA analysis on STRB performance.

A correlation analysis showed that SLR correlated negatively with DS (−0.64) and VS/DS (−0.53) factors. This may seem contradictory to the trends observed in the comparison between Temperate type 1, Temperate type 2, and Tropical climates, but it most likely shows that there is room to increase SLR in Temperate type 1 and Temperate type 2 climates without affecting performance significantly (Table 3). Similar results were found in previous studies of typical STRBs conducting sensitivity analysis on the impact of variation of sludge loading rate on DS content (Stefanakis and Tsihrintzis, 2012a; Kołecka et al., 2019).

In addition, feed duration has a negative correlation with DS (−0.55), namely, opting for a longer period of feeding results in lower DS, which was mentioned in pilot studies as well (Caicedo et al., 2015; Boruszko, 2018). On the contrary, operational rest has a positive correlation with DS (0.69); therefore, to achieve higher DS, operational rest should increase (Korboulewsky et al., 2012).

3.3. STRB media characterization

One of the key factors in the efficiency of the dewatering process is the filtration material (Brix, 2017). Through the previous studies, various kinds of materials have been used including sand and gravel (used in 89 % of the studies). The media configuration in terms of the number of layers is the other factor that influences the overall performance of the drying process (Nielsen and Larsen, 2016). The MA showed that 55 % of the previous studies (20 out of 36 studies) applied two layers of filtration material of different sizes (Brix, 2017). The substrates used for the top layers are fine sands while coarse gravels are used in the bottom layers (Nielsen, 2005). Also, 39 % of the studies have used three layers of filtration (Kengne and Tilley, 2014). Only 3 % of the studies used one layer and 3 % applied four layers (Cui et al., 2015; Wang et al., 2019, 2020; Ma et al., 2020; Liang et al., 2021). The size of cobbles used in the previous studies was in the range of 28 to 49 mm (95 % level of confidence), with the size of grains between a minimum of 0.2 and a maximum of 400 mm.

Other substrates can be used in the media to influence filtration efficiency, including slag and quartz along with sand and gravel, which were applied in 6 % of the studies (Cui et al., 2015; Wang et al., 2019, 2020; Ma et al., 2020; Liang et al., 2021). Other substrates used in combination with sand and gravel are, for instance, peat and crushed pine bark, wood shaving, graphite particles, and granular activated carbon (Gustavsson and Engwall, 2012; Uggetti et al., 2012a; Wang et al., 2021; Zhong et al., 2021). These materials are used to increase the filtration capacity and the rate of organic matter decomposition (Wang et al., 2021). Graphite

Table 2
A summary of MA analysis on STRB performance.

Parameters type	Parameters	Statistics	Unit	Climate condition				
				Temperate type 1	Temperate type 2	Tropical	Arid	Polar
Performance	DS during feeding	Min	%	11	16.25	11.5		
		Max		92.6	57.9	71		
		Mean		33	35	40	[a]	[a]
		Lower limit		26.04	26.96	29.12		
		Upper limit		39.83	42.88	50.73		
		No of studies	Number	27	13	14		
	DS after resting	Min	%	16.85				
		Max		94.5				
		Mean		45	[a]	[a]	[a]	[a]
		Lower limit		30.08				
		Upper limit		60.71				
		No of studies	Number	11				
	VS/DS during feeding	Min	%	15	35.5	17.4		
		Max		67	66	62		
		Mean		53	55	42	[a]	[a]
		Lower limit		46.64	48.2	33.27		
		Upper limit		58.42	61.31	50.96		
		No of studies	Number	17	12	11		
	VS/DS after resting	Min	%	14				
		Max		61.15				
		Mean		39	[a]	[a]	[a]	[a]
		Lower limit		18.81				
		Upper limit		59.5				
		No of studies	Number	4				
	Sludge thickness	Min	cm/year	6	3	2		
		Max		79	33	11		
		Mean		26	10	6		
		Lower limit		17.14	5.67	4.55	[a]	[a]
		Upper limit		34.89	14.75	8.33		
		No of studies	Number	18	16	12		
	Sludge volume reduction	Min	%	60	81			
		Max		97	99.64			
		Mean		84	92	[a]	[a]	[a]
		Lower limit		73.34	88.01			
		Upper limit		94.12	95.89			
		No of studies	Number	8	8			

[a] Less than 3 studies.

particles and granular activated carbon can be used alone or with gravel to generate power from the organic matters of the accumulated sludge in the STEW system (Wang et al., 2021; Zhong et al., 2021). A few numbers of studies have also filled the media with earthworms to enhance the dewatering capacity and more particularly to reduce the volume of accumulated sludge and improve the fertilization value of the final residuals (Calderón-Vallejo et al., 2015; Chen et al., 2016; Chen and Hu, 2019; Hu and Chen, 2018; Hu et al., 2020; Zhong et al., 2021). Two types of earthworms were used, including *Lumbricus terrestris* (Calderón-Vallejo et al., 2015) and *Eisenia fetida*, the last was the most applied macro-organisms in previous earthworm STRBs (Chen et al., 2016; Chen and Hu, 2019; Hu and Chen, 2018; Hu et al., 2020; Zhong et al., 2021).

3.4. STRB vegetation

The plant species used over the media are another crucial factor influencing dewatering performance and by-product quality (Kołecka et al., 2018). Therefore, selecting the right plant species based on climate conditions, and natural and ecological capacities has been a challenge through experiences. A list of planted species used in previous studies is organized in Table 4. It is shown that the application of native plant species causes an improvement in the resilience, performance, efficiency, and sustainability of a reed bed site (Brix, 2017).

Our statistical analysis reveals that *Phragmites australis* (common reed, *P.a*) was adopted in almost two-thirds of the cases, used in 76 either pilot or large scale of the facilities, and in total 23 different species have been tested in previous studies. *Typha latifolia* (*T.l*) was the second most popular species in previous studies and the more common reeds after *P.a* and *T.l* were *Typha angustifolia*, *Canna indica*, *Cynodon dactylon pers*, *Echinochloa pyramidalis* (*Antelope grass*) and *Cyperus papyrus*. Based on Table 4, 13 species were adapted to Tropical climates while five species for Temperate type 1 and four species for Temperate type 2 climates were tested. Four types of plant species were used in the Arid climate while three types of plants were tested in the Polar climate. Some plant species listed in Table 4 were used only one time; therefore, future investigations are necessary to find out how these species perform in the dewatering process in different climates.

It is also important to select the right density of reeds for the plantation, especially on the startup day of operation, and in fact, plant density can influence the time of reed bed adaptation to the engineered environment and to the commissioning period (Nielsen, 2005). Provided that the right density of reed is considered, the overall design efficiency of the reed bed maintains from the first day of operation, and the time from plantation to the maximum STRB performance (commissioning period) shortens; however, plants propagate and proliferate by the time and the introduction of raw sewage sludge (Brix, 2017). On the other hand, the increase in planted tufts in the reed bed leads to higher costs, therefore cost/efficiency should be optimized. Our statistical analysis shows that 14 studies used less than

Table 3
Correlation between parameters of STRB operation and efficiency (DS and VS/Ds are the values during feeding).

Parameters		Operational		
		SLR	Feed duration	Operational rest
Efficiency	DS	−0.64	−0.55	0.69
	VS/DS	−0.53	−0.14	−0.20

Table 4
Plant species used in previous studies, based on climate conditions.

Plant species	No of applications					References
	Temperate type 1	Temperate type 2	Tropical	Arid	Polar	
Bambusa vulgaris				1		Osei et al., 2019
Cymbopogon nardus				1		Osei et al., 2019
Canna indica			3			Chen et al., 2016; Wang et al., 2021; Zhong et al., 2021
Cynodon dactylon pers			2			Calderón-Vallejo et al., 2015; Andrade et al., 2017
Echinochloa crus galli	1					Lienard et al., 1990
Echinochloa pyramidalis			2			Dodane et al., 2011
Cyperus papyrus			2			Kengne et al., 2009; Magri et al., 2016
Cyperus alopecuroides			1			El-Gendy and Ahmedb, 2020
Eichhornia crassipes			1			El-Gendy and Ahmedb, 2020
Water hyacinth			1			El-Gendy and Ahmedb, 2020
Phragmites australis	44	21	11		1	Hofmann, 1990; Burgoon et al., 1997; Edwards et al., 2001; Pempkowiak and Obarska-Pempkowiak, 2002; Nielsen, 2003; Nassar et al., 2006; Nielsen, 2007; Stefanakis et al., 2009; Troesch et al., 2009; Dominiak et al., 2011; Gustavsson and Engwall, 2012; Lechner, 2014; Caicedo et al., 2015; Kołecka et al., 2016; Tan et al., 2017; Masciandaro et al., 2017; Kim et al., 2018; Kołecka et al., 2018; Rozkošný et al., 2020; Wang et al., 2020; Velychko and Dupliak, 2021; Plestenjak et al., 2021; He et al., 2021
Panicum echinochloa		1				El-Gendy and Ahmedb, 2020
Oryza longistaminata				1		Kouawa et al., 2015
Sporobolus pyramidalis				1		Kouawa et al., 2015
Panicum repens		1				El-Gendy et al., 2017
Typha latifolia	2	3	4			Korboulewsky et al., 2012; Wu, 2014; Magri et al., 2016; Chen and Hu, 2019; Hu and Chen, 2018; Hu et al., 2020; Stefanakis and Tsihrintzis, 2011a; Uggetti et al., 2012a; Stefanakis and Tsihrintzis, 2012a
Typha angustifolia			3		1	Koottatep et al., 2005; Gagnon et al., 2013
Scirpus fluviatilis					1	Gagnon et al., 2013
Iris pseudacorus	1					Korboulewsky et al., 2012
Vetiveria zizanioides	1					Summerfelt et al., 1999
Zizaniopsis bonariensis			1			Magri et al., 2016

five tufts per square meter while 14 studies planted between 5 and 20 tufts per square meter. Three studies used >20 tufts per square meter (Osei et al., 2019; Hu et al., 2020; El-Gendy and Ahmedb, 2020). The analysis suggests that on average six to ten tufts per square meter are used at the time of construction.

3.5. STRB removal efficiency

3.5.1. Heavy metals (HMs)

There have been several studies addressing the removal of Heavy Metals (HMs) from sludge in STRB systems. The main factors studied include vegetation, size of filtration materials, SLR, duration of final resting, and the quality of raw sludge (Stefanakis and Tsihrintzis, 2012b; Zhang et al., 2012). It was found that HMs were accumulated and bounded in residual sludge (Stefanakis and Tsihrintzis, 2012b; Caicedo et al., 2015; Boruszko, 2018). Comparisons between HMs in influent and effluent of STRBs showed that the mean contents of metals in the accumulated sludge are lower compared to the influent (Stefanakis and Tsihrintzis, 2012b). HM concentration can increase by the depth of sludge (Stefanakis and Tsihrintzis, 2012b; Caicedo et al., 2015; Boruszko, 2018; Chen and Hu, 2019) and Uggetti et al. (2012b) reported that the HMs in bio-solids was negligible due to the low concentration in the influent.

The concentration orders of HMs in the residual sludge (fed by domestic raw sludge) were Pb < Ni < Cr < Cd < Fe < Cu < Zn < Mn in the study of Stefanakis and Tsihrintzis, 2012b, while Kengne et al. (2009) Cd < Ni < Cr < Se < Pb < Mn < Cu < Zn. Begg et al. (2001) also found a similar order to Mb < Cd < Cr < Br < Pb < Mn < Ni < Zn < Cu < Fe. Thus, Zn, Cu, and Mn seem to be the predominant elements. The accumulation of Cr, Cd, Pb, and Ni was found slowly, which decreased with time while the accumulation of Cu, Mn, Zn, and Fe was reported faster (Stefanakis and Tsihrintzis, 2012b). The seasonal effect has been shown as an effective factor in increasing the concentration of Cu, Mn, and Fe during the summer due to higher dryness of sludge while Cr, Cd, Zn, Pb, and Ni contents were decreased. It is found that the concentration of all HMs were below legal limits for land applications (Begg et al., 2001; Obarska-Pempkowiak et al., 2003; Uggetti et al., 2009; Kengne et al., 2009; Stefanakis and Tsihrintzis, 2012b; Caicedo et al., 2015; Kołecka et al., 2017; Boruszko, 2018). In STEW systems, the HM removal efficiency was satisfactorily led to the direct use of residual sludge in agriculture, and it is reported that Cd, Ni, Pb, Ti, As, Co, Cr, Cu, and Mn reduced by 81.12, 30.02, 45.70, 23.10, 50.28, 32.39, 39.76, 41.80 and 12.97 %, respectively (Wang et al., 2021).

Studies showed that HMs accumulated in upper and below-ground parts of plants and the biomass of the plants would increase year by year (El-Gendy et al., 2017); therefore, the uptake by the plants will gradually increase (El-Gendy and Ahmedb, 2020). The bioavailability of HMs in soil and plants depends on several factors including soil pH, plant species and their cultivars, growth stage, bio-solids source, soil condition, and the chemistry of the element (Warman and Termeer, 2005). It was found that the HM concentrations in plant biomass were, in decreasing order, Cr > Fe > Zn > Mn > Cu > Pb > Ni > Cd (Stefanakis and Tsihrintzis, 2012b). The maximum HMs concentration was in the roots, followed by leaves and stems (Stefanakis and Tsihrintzis, 2012b; Cheng et al., 2002). Caicedo et al. (2015) obtained comparable results, with the highest concentrations of HMs in the roots and then in the rhizomes and aerial parts. In the study of Caicedo et al. (2015) the order of retention was found as Sb < Hg < Cd < Mo < Co < Ni < Pb < Cr < Mn < Cu < Zn < Fe in roots, Sb < Hg < Cd < Mo < Ni < Pb < Co < Cr < Cu < Mn < Zn < Fe in the rhizomes and Sb < Hg < Cd < Mo < Pb < Ni < Co < Cr < Cu < Mn < Zn < in the shoots or aerial parts of the plant biomass. Planted and unplanted units were compared and revealed that vegetation has a profound impact on the reduction and mobility of HMs through the provision of microbial contact surfaces (Stefanakis and Tsihrintzis, 2012b) although the vegetation accounted for only 3 % of HMs accumulation (Stefanakis and Tsihrintzis, 2012b). The Bio-Concentration Factor (BCF = HMs content in plants/HMs content in raw sludge) of HMs was found with no statistical difference between *P. australis* and *T. angustifolia* ($p > 0.05$) (Chen and Hu, 2019).

Previous studies on earthworm STRB showed that earthworms are effective in the accumulation of HMs (Calderón-Vallejo et al., 2015; Chen et al., 2016; Hu and Chen, 2018; Hu et al., 2020). It is found that the reason for HMs enrichment by earthworms in the accumulated sludge was due to the activities of enzymes in earthworms (Chen and Hu, 2019). Bio-Accumulation Factor or BAFs (HMs content in earthworms/HMs content in raw sludge) were found as Cd > Mn > Ni > Zn > Pb > Cr > Fe (Chen and Hu, 2019). The difference between earthworm STRB and typical STRB in terms of heavy metal contents during the feeding period was not statistically significant although it was significantly different after the resting period (Hu et al., 2020). Earthworm STRB showed a better HMs accumulation in sludge depending on the density of earthworms of which higher density will result in a higher HMs accumulation (Hu et al., 2020). Earthworms provided a positive effect on the accumulated sludge characteristics in STRBs (Hu et al., 2020). Further investigations require to find the role of earthworms in the bioavailability of HMs in residual sludge, plants, and effluent.

3.5.2. Nutrients and nitrogen components

STRB has been shown effective in the removal of different nutrients and nitrogen components in previous studies, although it is highly dependent on the quality of the fed raw sludge (Burgoon et al., 1997; Moss et al., 2002; Bianchi et al., 2011; Uggetti et al., 2012b; Korboulewsky et al., 2012; Andrade et al., 2017; Osei et al., 2019). One of the major nutrients in influent sludge is nitrogen, which is the removal target of most WWTPs, and the order of nutrients was found as Ca > P > S > K > Mg in the accumulated sludge (Caicedo et al., 2015). The concentration of nutrient elements can increase with the time of STRB operation; however, it was found that there is a decreasing tendency along with the layers of the vertical profile of the accumulated sludge due to mineralization, ammonification, and plant uptake (Peruzzi et al., 2009; Melidis et al., 2010; Zhang et al., 2012; Uggetti et al., 2012b; Caicedo et al., 2015; Hu and Chen, 2018). The variation of potassium (k) was found negligible after the treatment (Uggetti et al., 2012b). Depending on the nutrient concentration in the accumulated sludge, its application to agricultural land can be considered (Hu and Chen, 2018).

The concentration of nutrients was found in a common trend with Total Organic Carbon (TOC) concentration along with the vertical profile of biosolids (Caicedo et al., 2015). Total Kjeldahl Nitrogen (TKN) reduced from the influent to the sludge accumulated (Uggetti et al., 2009). TKN concentration of residual sludge was reduced by up to 66 % in previous studies (Stefanakis et al., 2009; Arroyo et al., 2018; Osei et al., 2019). It was observed that there were reductions for NO_2-N and NO_3-N of 86.4 and 28.7 % in residual sludge, respectively (Stefanakis et al., 2009). NH_4-N reduction was reported in STRB systems as well (Arroyo et al., 2018).

Low phosphorus concentration was found in treated sludge due to phosphorus retention in plants (Peruzzi et al., 2009). Total phosphorus (TP) reduction of up to 80 % was reported in some studies depending on the presence of plants and earthworms (Begg et al., 2001; Stefanakis et al., 2009; Chen et al., 2016; Osei et al., 2019). A study of plant species' effect on P removal in typical STRB showed that *Phragmites*, *Typha*, and *Iris* were responsible for 17, 12, and 6 % of phosphorus removal from the sludge, respectively (Korboulewsky et al., 2012). In the earthworm STRBs, it was shown that the sum of TN, TP, and TK was significantly lower than the STRBs without earthworms (Hu and Chen, 2018). Earthworm movements increase voids in the accumulated sludge, enhancing oxygen availability in the bed, which accelerate TN, TP, and TK conversion and absorption by microorganisms in sludge (Brix, 2017; Chen et al., 2016; Gagnon et al., 2013). Investigations of STEW showed that TN/DS ratio in accumulated sludge after the resting period is between 2.86 and 2.96 % (Wang et al., 2021), which is lower than the value obtained for typical STRB of 3.18 to 6.4 % TN/DS (Peruzzi et al., 2009; Melidis et al., 2010). Therefore, the TN/DS of residual sludge is low, and the TN/DS of STEW is less than the total Nitrogen of STRB systems. In terms of nutrient concentration, extracted sludge from STEW can be used for agricultural applications (Wang et al., 2021). Also, TP concentration reduced in STEW up to 54.88 % while TP/DS of STRBs showed a slightly lower reduction of 50.24 % after the resting period (Wang et al., 2021). Among the effective factors of P removal, plant uptake is the major contributor of 68 % in the STEW system (Wang et al., 2021).

3.5.3. Drain water quality

The water drained out (called also rejected water or leachate) of STRB has been monitored in previous studies as well, including several parameters from HMs, nitrogen components, organic matter, pathogenic organisms, nutrients to emerging pollutants (Liénard and Payrastre, 1996; Edwards et al., 2001; Begg et al., 2001; Cooper et al., 2004; Koottatep et al., 2005; Stefanakis et al., 2009; Gustavsson and Engwall, 2012; Calderón-Vallejo et al., 2015). The removal efficiency of STRB reported for Total Suspended Solids (TSS) and Chemical Oxygen Demand (COD), was higher than 85, 85, 76, and 66 % for the mesocosms planted with *Phragmites*, *Typha*, *Iris*, and unplanted one, respectively (Burgoon et al., 1997; Begg et al., 2001; Korboulewsky et al., 2012; Chen et al., 2016; Magri et al., 2016; Kim et al., 2018; Wang et al., 2021). STRB showed high efficiency in the removal of TKN and TP with >95 % reduction from the inlet to the outlet points (Kim et al., 2018). The effluent quality of the STRB has been within the regulatory standards of the previous study that needs no further treatment (Begg et al., 2001). Chen et al. (2016) showed that the removal efficiency of the systems with earthworm layer is quite higher than that of STRB systems. It was found that the HM concentration of the drained water is <10 % of the concentration in influent for the typical STRB (Stefanakis and Tsihrintzis, 2012b; Chen and Hu, 2019). The removal efficiency of HMs in the leachate of STRBs with earthworms was significantly different from that of STRB and unplanted STRB (Chen and Hu, 2019).

To explore whether the dewatered accumulated sludge is safe to reuse for land applications, some studies addressed the presence of fecal pathogens (Koottatep et al., 2005; Kengne et al., 2009; Uggetti et al., 2009; Wang et al., 2021). Kengne et al. (2009) found that *Ascaris lumbricoides* is the most widespread species of *helminth* in residual sludge followed by *Trichuris trichiura* varying based on the depth of the sludge, where the most counted *helminth* was detected in the upper layers. The resting time had a negative correlation with the number of fecal species (Kengne et al., 2009). Uggetti et al. found that *E. coli* is present in the residual sludge decreasing with the time of resting while *Salmonella* specie was not detected in the final accumulated sludge (Uggetti et al., 2009). Egg viability was found <10 % and egg concentrations were <6 eggs per gram DS as well (Koottatep et al., 2005). In most studies, it was stated that effluent can be reused without leachate disinfection (Koottatep et al., 2005; Stefanakis et al., 2009; Gustavsson and Engwall, 2012; Calderón-Vallejo et al., 2015).

4. Conclusion

In this paper, 73 studies were selected and reviewed of which 66 studies of Sludge Treatment Reed Beds (STRB) were used to conduct a Meta-Analysis (MA) on a global scale since 1990. Most studies have been concentrated in Europe and China, and were mostly pilot-scale studies, and domestic raw sludge was tested stemming from combined primary and secondary surplus sludge. In addition to typical STRB design, seven studies with different designs were identified, including earthworm STRB, STEW, earthworm STEW, and intensified system that can potentially improve dewatering performance and resource recovery as well as power generation. Through the climate categorization of STRB studies in MA, we found the average Sludge Loading Rate (SLRs) for Temperate type 1, Temperate type 2, Tropical, Arid, and Polar climates were 50, 70, 101, 80, and 30 Kg.DM.m^{-2}.year^{-1}, respectively, while for the earthworm STRB, it was 120 Kg.DM.m^{-2}.year^{1}. MA showed that average DS during the feeding of 33, 40, and 45 % can be obtained in Temperate type 1, Temperate type 2, and Tropical climates while the average DS after feeding was 45 % for Temperate type 1 and 75 % for Temperate type 2, with only one study in Tropical climate obtaining 59 %. Studies performed on the earthworm STRB, STEW, and earthworm STEW showed that an improvement in the typical STRB was observed. The MA evinced that the height of accumulated sludge can increase in the order of 26, 10, and 6 cm per year for Temperate type 1, Temperate type 2, and Tropical climates, respectively while it is around 2 cm per year in the available studies of earthworm STRB, STEW and earthworm STEW systems (a reduction of 85 % of the accumulated sludge volume after final resting and stabilization process). MA showed that in most studies natural cobbles were used for reed bed media with three layers of substrate sizing from 49 to 28 mm while other studies have recently used graphite particles and granular activated carbon to generate power out of organic matters. A total of 23 plant species were identified in the reviewed studies in which *Phragmites Australis* was adapted in two-thirds of the cases. Plants were found effective in the up taking of different pollutants particularly nutrients while they are accelerating the removal process of other pollutants as well. The STRB technology was also found highly effective in removing HMs, nutrients, nitrogen components, pathogens, and emerging pollutants from sludge and drained water.

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CRediT authorship contribution statement

Amir Gholipour: Meta Analysis, Data collection, Data analysis, Manuscript organization, Writing original draft of the manuscript, Visualization, Funding acquisition.

Rita Fragoso: Data curation, Validation, Review & Editing, Visualization, Supervision.

Elizabeth Duarte: Data curation, Validation, Review & Editing, Visualization, Supervision.

Ana Galvão: Meta Analysis, Conceptualization, Data analysis, Manuscript organization, Validation, Writing – Review & Editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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