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The role of sludge treatment reed beds in ecosystem services delivery and circular economy implementation – Case studies from Denmark and Poland

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ABSTRACT

This study explored the performance and multifunctionality of sludge treatment reed bed (STRB) systems as a nature-based solution for sewage sludge management. STRBs were evaluated at six locations in Denmark and Poland, varying in operational age, design, and sludge feeding frequency. The analysis focused on sludge quality parameters, including dry matter (DM), organic matter (OM), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and selected heavy metals (Cd, Pb, Ni, Cr, Cu, Zn). This article aimed to critically evaluate the potential of STRB systems in the context of an evolving regulatory framework, emphasizing their role in delivering ecosystem services and advancing the circular economy. Particular attention was given to the influence of operational parameters on the quality and valorization potential of the treated sludge. Results revealed a strong influence of operational factors, particularly resting periods and system age, on sludge stabilization and nutrient recovery. For example, dry matter content ranged from 9.3% in recently loaded beds to 53.1% in long-rested systems, while organic matter decreased to as low as 28.6% in aged, inactive beds. Most sludge samples met the EU thresholds for nitrogen (0.5–3.0%) and phosphorus (0.5–3.5%) in organic fertilizers, with phosphorus concentrations reaching up to 4.7%. Heavy metal levels remained below legal limits across all sites. STRBs were also assessed for their contribution to ecosystem services using the Common International Classification of Ecosystem Services framework. Findings confirm that STRBs offer provisioning, regulating, and cultural services, while simultaneously aligning with circular economy principles through nutrient cycling, low energy use, and decentralized infrastructure.

Keywords: sludge treatment reed beds; nature-based solutions; sewage sludge; ecosystem services; circular economy.

INTRODUCTION

In recent years, the management of sewage sludge has become an increasingly pressing issue due to stricter environmental regulations, rising treatment costs, and the growing demand for sustainable solutions aligned with climate and resource efficiency policies. Conventional sludge handling methods, such as mechanical dewatering, incineration, or landfill disposal, are often energy-intensive and generate secondary environmental impacts. Consequently, there is a growing interest in nature-based solutions (NbS) that align with circular economy principles as well as offer co-benefits beyond basic treatment, including, among other things, biodiversity support, carbon sequestration, and landscape integration (Durdević, et al. 2022; Tan et al., 2024)

NbS contribute to ecosystem services (ES), defined as the benefits that people derive from ecosystems. These services can be systematically classified using the Common International Classification of Ecosystem Services (CICES), which provides a structured framework for describing the contributions of ecosystems to human well-being. While CICES initially focused on biotic outputs, the latest version (V5.2) incorporates abiotic ecosystem contributions as well, allowing users to include the services derived from both living and non-living systems (Haines-Young and Potschin, 2025). CICES focuses on final ecosystem services, meaning those that are directly consumed or used by humans. This classification does not include ecosystem processes themselves (e.g., photosynthesis, nutrient cycling), but only their effects that have a direct impact on human well-being.

CICES distinguishes the following sections:

- provisioning services – these include the material goods provided by ecosystems, such as food, water, timber, biological materials, and genetic resources. These are the resources directly used by humans.
- regulation and maintenance services – these cover ecosystem functions that help maintain environmental quality and the stability of natural processes – for example, climate regulation, air and water filtration, pollination, erosion control, and the regulation of pests and diseases;
- cultural services – these refer to the non-material benefits that people derive from ecosystems, such as recreation, landscape aesthetics, spiritual values, cultural identity, and artistic or scientific inspiration (Haines-Young and Potschin, 2025).

Understanding ES through classifications such as CICES provides a structured framework for recognizing the value of natural systems to human well-being. However, in order to preserve these services and ensure their long-term availability, it is necessary to rethink how resources are used, managed, and cycled in the economy. In this context, the circular economy (CE) concept has gained significant traction in both academic and policy fields. According to the European Parliament (2023), it represents a model of production and consumption based on sharing, leasing, reusing, repairing, refurbishing, as well as recycling existing materials and products to extend their lifecycle. This approach contrasts with the traditional linear economy and aims to reduce waste generation while maximizing the value retained in materials through recovery and reuse (Ellen MacArthur Foundation, 2013).

One particularly promising NbS is the sludge treatment reed bed (STRB) system. This low-maintenance technology integrates dewatering, mineralization, and stabilization of sewage sludge in a single treatment stage. In STRBs, sludge with low dry solids content (typically 0.5–1%) is applied in layers onto above-ground basins or concrete structures planted with common reed (*Phragmites australis*). Treatment cycles usually last between 8 and 12 years, although some systems remain operational for up to 15 or even 20 years (Nielsen, 2003, Kołecka and Obarska-Pempkowiak, 2013).

Sludge may be introduced directly from aeration tanks or after homogenization in a storage tank. Flow is directed into multiple zones of the reed bed, with only one zone active at a time while the others regenerate (Kołecka et al.,2018). These systems offer multiple advantages: they operate with low energy input and minimal operational costs, reduce greenhouse gas emissions, and integrate well into natural or rural landscapes. When managed under optimal conditions, STRBs produce stabilized sludge that meets quality criteria for agricultural application. The quality of treated sludge is strongly influenced by operational parameters, including the rate and frequency of sludge application, the thickness of applied layers, and the resting time of basins. Extended resting periods enhance microbial activity and humification, improving sludge maturity and hygienic safety (Al-Rashdi et al., 2024, Kołecka et al., 2017, Kowal et al., 2021)

Recent legislative developments in the European Union and Poland have created a favorable context for the adoption of natural sludge treatment systems. The revised EU Urban Wastewater Directive 2024/3019 extends treatment requirements to smaller agglomerations (≥1000 population equivalent) and emphasizes resource recovery, including phosphorus and energy (European Commission, 2024). In parallel, Poland is set to amend its Regulation on Sewage Sludge from January 2026, formally recognizing humification (defined as sludge resting for at least 90 days) and drying to below 30% moisture content as valid stabilization methods *(Regulation of the Minister of the Environment, 2015; Regulation of the Minister of Climate and Environment, 2021).* These legal frameworks align closely with STRB operational principles, simplifying compliance and enhancing the feasibility of such systems in decentralized wastewater treatment contexts.

This article aimed to critically evaluate the potential of STRBs in the context of an evolving regulatory framework, emphasizing their role in delivering ecosystem services and advancing the circular economy. Particular attention is given to the influence of operational parameters on the quality and valorization potential of the treated sludge.

MATERIAL AND METHODS

Material

The analyzed sewage sludge was dewatered and stabilized in STRBs located in 3 objects in

Denmark and 3 objects in Poland. These objects differed, among other things, in terms of operational period, number of basins, and feeding frequency. Their characteristics are presented in Table 1.

In each of the analyzed objects, sludge samples were collected from a single plot. The samples were taken using a specialized sampler (Figure 1) from six points and then averaged.

Methods

In residue sewage sludge from STRBs, the following parameters were analyzed: dry matter (DM), organic matter (OM), total Kjeldahl nitrogen (TKN), total phosphorus (TP) as well as selected metals, included cadmium (Cd), lead (Pb), nickel (Ni), chromium (Cr), copper (Mg), and zinc (Zn).

Determinations of DM, OM, as well as TKN and TP concentrations were carried out following the applicable standards (PN-EN 12879:2004, PN-EN 16169:2012, PN-C-04537-14:1998).

The heavy metal concentrations in the sludge were determined using atomic absorption spectrophotometry after prior mineralization of the samples (PN-EN 13657:2006).

RESULTS AND DISCUSSION

Sewage sludge quality

Table 2 presents the average dry matter content and standard deviation for selected STRBs from Denmark and Poland. Dry matter content is an important indicator of sludge compaction and maturation conditions..

Analysis of data from selected STRBs revealed a significant influence of system age, time since last feeding, sludge type, and feeding frequency on dewatering efficiency. Older facilities, such as Inwałd (17 years) and Nakskov (15 years), exhibited higher dry matter content (33.03% and 28.5%, respectively), indicating more effective dewatering due to long-term compaction and mineralization. In contrast, younger systems like Gniewino (6 years) and Helsinge (9 years) showed lower dry matter values (9.3% and 20.7%, respectively), which can be attributed to their shorter operational periods. However, the key factor affecting dry matter content was the time since the last feeding. The facilities that had not been fed for a longer period, such as Nadole (3 years, 53.07% DM), Inwałd (2 years, 33.03%), and Rudkobing (1 year, 29.3%), achieved significantly higher dry

Table 1. Characteristics of the analyzed STRBs

Location	Operational period,	Time since last feeding on the sampling day	Number of basins	Total area, m²	Type of sewage sludge	Feeding frequency	Remarks
Denmark							
Rudkobing	13	1 year	8	5 000	Surplus	Regularly every 2–3 months	System was not feeding during last 1 year
Nakskov	15	1 month	10	900	Surplus	Regularly every 2–3 months	
Vallo	7	2 months	8	3 867	Surplus	Regularly every 2–3 months	
Helsing	9	14 days	10	10 500	Surplus	Regularly every 2–3 months	
Poland							
Gniewino	6	21 days	6	2 400	Surplus	Every 2–3 weeks during the growing season	
Nadole	9	3 years	2	150	Surplus	Every 3–4 weeks during the growing season	System was not feeding during last 3 years
Inwałd	17	2 years	1	375	Primary	Once a year/ two years	System was not feeding during last 2 years

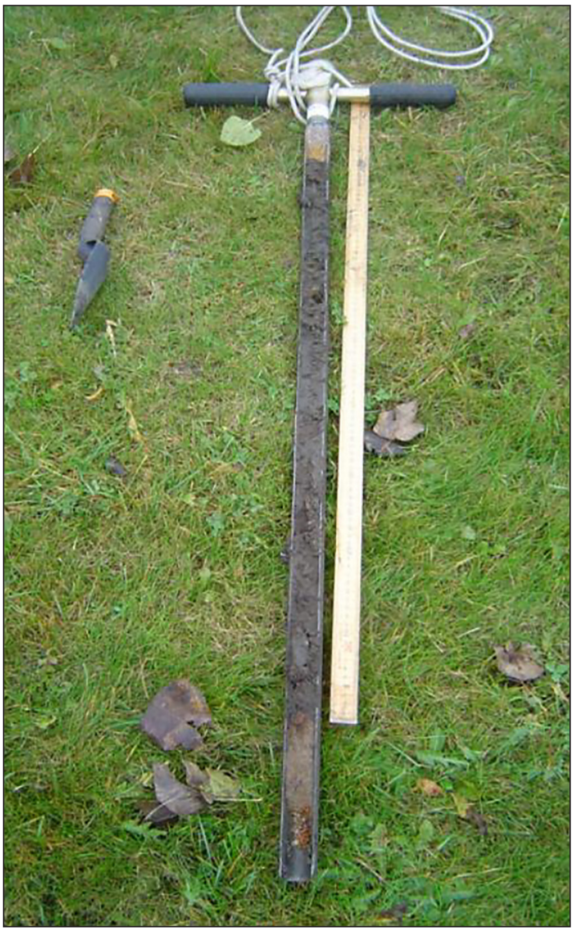

Figure 1. Sampler for sewage sludge sample collection

matter levels than the systems that had been fed recently (e.g., Gniewino – 21 days, 9.3%). This supports the hypothesis that longer resting periods enhance dewatering processes. These findings are consistent with recent literature. According to Huong et al. (2024), the dry matter content in STRB systems depends on sludge layer thickness, resting time, and climatic conditions, and under optimal conditions, 30–40% DM can be achieved. Other studies (Nielsen and Stefanakis, 2020) confirm that in well-designed and operated STRB systems, dry matter content can exceed 40%, particularly in long-seasoned layers.

Table 3 presents the average organic matter content and standard deviation for selected STRBs from Denmark and Poland. Organic matter content is a key indicator of sludge stabilization and biological activity within STRB systems. A decrease in organic matter reflects ongoing mineralization processes and improved sludge maturity.

Similar to DM content, OM levels in sewage sludge were significantly influenced by system age and the time since the last feeding. Older facilities such as Rudkobing (13 years), Nakskov (15 years), and Inwałd (17 years) exhibited moderate OM values (42%, 44.1%, and 41.6%, respectively), confirming that extended operation promotes organic matter degradation and mineralization. The lowest OM content was observed in Nadole (28.6%), which had not been fed for three years. The absence of fresh sludge input allowed for intensive biological stabilization and mineralization. In contrast, regularly fed systems such as Vallo (46%) and Gniewino (71%) showed significantly higher OM levels, indicating the presence of fresh, non-stabilized sludge. The particularly high OM content in Gniewino (71%) confirms that the sludge is young and largely unprocessed. The weak mineralization was also influenced by operational issues that occurred at the facility.

Recent studies (Tan et al., 2024) have shown that in well-designed STRB systems, organic matter content can be reduced to below 30% through long-term mineralization and microbial activity, especially under the conditions favorable for aerobic degradation. Masciandaro et al. (2017) further confirmed that humification of organic matter occurs in deeper STRB layers, indicating advanced stabilization. Additionally, the use of modern techniques, such as 16S rRNA gene sequencing has confirmed the presence of key microbial groups (e.g., Proteobacteria, Bacteroidetes, Actinobacteria) responsible for organic matter degradation in STRBs (Kowal et al., 2021).

Table 4 presents the average TKN and TP content in sewage sludge from selected STRBs. Nitrogen and phosphorus concentrations in sewage sludge are key indicators of its agronomic value, particularly when used as an organic fertilizer.

The highest TKN concentration was found in Gniewino (5.43%), an object with a short

Table 2. Dry matter content in the sewage sludge from the selected STRBs in %

Object		Helsinge	Rudkobing	Nakskov	Vallo	Gniewino	Nadole	Inwałd
DM	Mean	20.7	29.3	23.6	26.1	9.30	53.07	33.03
	Standard deviation	2.6	3.5	2.9	2.7	1.35	5.22	6.83

Table 3. Organic matter content in the sewage sludge from the selected STRBs in % of DM

Object		Helsinge	Rudkobing	Nakskov	Vallo	Gniewino	Nadole	Inwałd
OM	Mean	41.1	42.0	44.1	46.0	71.00	28.63	41.60
	Standard deviation	2.9	2.3	2.0	4.3	1.14	7.31	7.19

operational period (6 years) and recent feeding (21 days). The elevated nitrogen content may indicate the presence of fresh organic matter rich in proteins, which has not yet undergone decomposition (Paganini et al., 2024). In contrast, the lowest nitrogen concentrations were observed in Nadole (1.33%) and Rudkobing (1.9%), which may suggest advanced mineralization and nitrogen reduction due to denitrification or bioaccumulation by plants (Liang et al., 2025). Inwałd, despite a long feeding interruption (2 years), maintains a moderate TNK concentration (2.17%), which may result from the specific characteristics of the raw sludge, such as its composition and stabilization level (Abdelrahman et al., 2023).

In terms of TP, the highest concentrations were found in Rudkobing (4.7%), Nakskov (4.1%), and Vallo (4.2%), which were subjected to regular feeding with surplus sludge. The high TP content is likely the result of chemical phosphorus precipitation applied at the wastewater treatment plants. The lowest TP concentration was observed in Inwałd (0.67%), which indicates potentially low phosphorus content in the primary sludge.

The findings of this study align well with current literature. For instance, Ugetti et al. (2011) reported comparable nutrient concentrations in the sludge treated within STRBs, with total nitrogen ranging from 1.8% to 4.9% and total phosphorus between 0.7% and 4.5%. These values reflect the typical nutrient accumulation patterns observed in long-term stabilized sludge.

According to Regulation (EU) 2019/1009, the desirable nutrient content in organic fertilizers is defined as follows:

- Nitrogen: 0.5–3.0% of DM,
- Phosphorus: 0.5–3.5% of DM.

Most of the analyzed sludge samples meet these criteria, particularly in terms of phosphorus content. Sludges from Gniewino, Nakskov, Vallo, Helsinge, and Rudkobing may be considered attractive organic fertilizers, especially as a source of phosphorus.

In STRBs, in addition to parameters such as DM, OM content, and nutrient levels (TKN, TP), the presence and behavior of metals represent an important environmental concern. These metals can accumulate in the sludge and pose a risk to soil quality, groundwater, and the health of humans and animals if the sludge is applied in agriculture.

Table 5 presents selected metal concentrations in the sewage sludge from the analyzed STRBs

In terms of metals, the concentrations observed in the analyzed STRBs show considerable variability and reflect both local conditions and sludge stabilization history. The highest Cd concentration was found in Inwałd (3.9 mg/kg DM), significantly exceeding values observed in other objects. Elevated levels of Pb were found in Nadole (38.7 mg/kg DM) and Inwałd (37.9 mg/kg DM), while Ni concentrations peaked in Nadole (32.5 mg/kg DM). The highest Cr content was also found in Nadole (90.7 mg/kg DM), with Gniewino (43.6 mg/kg DM) and Inwałd (86.3 mg/kg DM) showing similarly high values. Cu was most abundant in Helsinge (237.0 mg/kg DM) and Inwałd (230.1 mg/kg DM), while Zn reached its maximum in Inwałd (1110.7 mg/kg DM).

Table 4. Total Kjeldahl nitrogen and total phosphorus content in the sewage sludge from the selected STRBs in % of DM

Object		Helsinge	Rudkobing	Nakskov	Vallo	Gniewino	Nadole	Inwałd
TKN	Mean	2.0	1.9	2.4	2.2	5.43	1.33	2.17
	Standard deviation	0.1	0.2	0.3	0.3	0.29	0.30	0.23
TP	Mean	3.8	4.7	4.1	4.2	2.70	2.07	0.67
	Standard deviation	0.2	0.1	0.4	0.6	0.17	0.21	0.09

Table 5. Selected metal concentrations in the sewage sludge from the selected STRBs in mg/kg of DM

Object		Helsinge	Rudkobing	Nakskov	Vallo	Gniewino	Nadole	Inwałd
Cd	Mean	0.95	0.84	0.74	1.07	1.5	1.3	3.9
	Standard deviation	0.09	0.08	0.11	0.09	0.11	0.20	0.91
Pb	Mean	10.7	14.6	15.6	10.0	11.3	38.7	37.9
	Standard deviation	0.96	1.39	1.45	1.13	4.09	6.33	6.01
Ni	Mean	20.7	20.3	22.4	26.3	20.1	32.5	30.8
	Standard deviation	1.86	2.23	3.02	3.37	1.11	3.45	1.6
Cr	Mean	18.1	32.1	17.5	11.3	43.6	90.7	86.3
	Standard deviation	1.69	3.69	2.18	1.02	7.51	7.90	9.84
Cu	Mean	237.0	219.0	81.0	166.0	85.8	91.1	230.1
	Standard deviation	21.32	15.7	8.31	14.90	21.21	12.90	28.07
Zn	Mean	416.0	542.0	437.0	520.0	561.2	945.7	1110.7
	Standard deviation	37.49	52.81	39.38	46.81	21.21	79.08	111.90

These results are consistent with the findings from Nielsen et al. (2017) and Ugetti et al. (2011), who reported typical concentrations in STRB-treated sludge within the ranges of Cd: 0.5–1.2 mg/kg DM, Pb: 10–45 mg/kg DM, Ni: 15–35 mg/kg DM, Cr: 20–90 mg/kg DM, Cu: 80–250 mg/kg DM, and Zn: 400–1100 mg/kg DM.

Notably, none of the analyzed sludge samples exceeded the maximum permissible concentrations of heavy metals established by the Polish Regulation of the Minister of the Environment (Journal of Laws 2015, item 257), which defines the legal thresholds for the agricultural use of sewage sludge. This confirms the potential suitability of the tested materials for land application, provided that other agronomic and environmental criteria are also met.

Exploitation problems

Despite numerous advantages and the suitability of STRBs for small and medium-sized wastewater treatment plants, it is rarely used in Poland. This is primarily due to a lack of sufficient knowledge and experience among designers, who therefore do not recommend this solution to investors. Additionally, there is a shortage of Polish companies with experience in constructing this type of system.

Like any other solution, STRBs also have their drawbacks. Most importantly, they require a large surface area. The largest reed bed system in Kolding, serving 125,000 PE (Population Equivalent), covers an area of 6.2 hectares (Nielsen, 2003), which amounts to just under 0.5 m^2 per person. Moreover, time is needed for the system to reach full operational capacity, typically 2–3 years. During this period, the STRBs should be loaded with a reduced amount of sludge.

Although the construction of STRBs are relatively simple, achieving proper operational parameters requires a highly precise design and execution, especially regarding the drainage and ventilation system, as well as the quality and installation of the filter layers. Many errors are made in these areas.

Operational problems are often the result of mistakes made during the early stages of implementation, such as design, construction, or commissioning. The consequences of these errors often become apparent only after several years of operation. Figure 2 shows a reed bed system that has experienced operational issues.

Improperly constructed drainage and ventilation system, as well as incorrect composition of the filter layers, may lead to excessively long leachate drainage times. This, in turn, results in the development of anaerobic conditions and improper system performance. Incorrect system start-up procedures can also negatively affect plant development. If the reeds do not take root properly, they may not be able to handle the design sludge load during full operation.

Operational problems may also arise from an insufficient number of beds in the system, which do not provide a sufficiently long resting period between subsequent sludge applications. One of the most common and serious operational issues is the application of excessively high sludge doses. Operational issues may also be caused by poor sludge quality. The factors that negatively affect sludge dewatering and stabilization include a high fat content, which is particularly detrimental as it often leads to a number of secondary problems. These include an increased content of volatile solids, a higher sludge volume index, deteriorated sedimentation properties, and the proliferation of filamentous bacteria.

When using low-quality sludge, it is necessary to reduce the applied sludge dose by up to 50%. As a consequence, this leads to an increased required area of the system (Nielsen, 2003, 2011; Kołecka and Obarska-Pempkowiak, 2013; Brix, 2014, 2017).

The ecosystem and circular functions of STRBs

STRBs combine technical efficiency with ecological functionality, making them well-aligned with circular economy principles. These systems not only provide a sustainable solution for sludge stabilization and dewatering but also deliver a broad spectrum of ES.

Within the category of provisioning services, STRBs generate biologically stabilized sludge enriched with essential nutrients such as nitrogen and phosphorus. TKN concentrations in DM ranged from 1.33% to 5.43%, and TP from 0.67% to 4.7%, with most samples meeting the requirements of EU Regulation 2019/1009 for organic fertilizers. Particularly promising phosphorus sources were identified in STRBs operating in Gniewino, Nakskov, Vallo, Helsinge, and Rudkobing. The low concentrations of heavy metals further enhance the agronomic value and safety of the sludge for land application. Thus, STRBs contribute to provisioning subgroups related to biomass supply, nutrient resources, and organic substances usable directly by humans, reinforcing material cycling in local agroecosystems.

In terms of regulation and maintenance services, STRBs fulfill key ecological functions that underpin environmental quality and natural stability. OM decomposition is achieved through interactions between wetland vegetation, notably *Phragmites australis*, and soil microbial communities. OM content decreased to 28.63% in Nadole and 41.60% in Inwałd, indicating advanced stabilization. DM content ranged from 9.30% in Gniewino to 53.07% in Nadole, reflecting the differences in dewatering performance and sludge maturity. STRBs effectively reduce contaminants while maintaining full compliance with EU limits for heavy metals (Cd, Pb, Ni, Cr, Cu, Zn) across all tested objects. These functions align with the regulation subgroups of waste decomposition and detoxification, water quality regulation, soil formation and stabilization, life-cycle maintenance as well as habitat provision, and climate regulation. Their passive operation, which relies on natural evapotranspiration and microbial processes, results in minimal energy use and a low carbon footprint, further supporting the climate-related regulatory services.

Beyond their technical and ecological functions, STRBs also contribute to cultural ES by offering

Figure 2. STRB in Gniewino, which experienced operational problems in 2017 (photo: Gniewino WWTP, Dariusz Rohde)

non-material benefits. Their natural, wetland-like appearance enhances landscape aesthetics, especially in rural and peri-urban areas. As demonstration sites for ecological engineering, STRBs serve educational and scientific purposes, fostering environmental awareness and innovation in sustainable wastewater management. Moreover, their decentralized nature and reliance on local resources strengthen community identity and promote regional narratives of ecological responsibility. These qualities correspond to the cultural subgroups related to visual and aesthetic value, educational and inspirational significance, and cultural identity.

STRBs exemplify the multifunctional systems that integrate sludge treatment with the delivery of diverse ES. They offer tangible environmental, agronomic, and social benefits, making them effective tools for advancing sustainable development goals, enhancing local ecological resilience, and operationalizing circular economy strategies through nature-based infrastructure.

STRBs also offer a tangible and effective application of CE principles within the water and wastewater management sector. These NbS contribute to sustainable resource use, emissions reduction, and decentralized infrastructure development. Their operation supports multiple pillars of CE, including material cycling, waste minimization, and local resilience.

One of the core principles of the circular economy is the closing of material cycles. STRBs facilitate this by enabling *in situ* transformation of sewage sludge into a stabilized, nutrient-rich material suitable for agricultural reuse. The biological stabilization processes that occur within the beds, driven by plant and microbial interactions, convert the sludge into a product that returns valuable nutrients (TKN, TP) back into the soil system. This nutrient recovery reduces dependency on synthetic fertilizers, supports soil fertility, and aligns with the EU ambitions for resource efficiency and phosphorus reuse. By reintroducing these nutrient elements into the agroecosystem, STRBs help maintain natural nutrient cycles and reduce the environmental footprint of conventional sludge handling methods.

Another essential aspect of circularity is minimizing waste, energy use, and emissions across system boundaries. STRBs are inherently low-input systems that do not require external energy for sludge treatment operations. They function passively, relying on solar-driven evapotranspiration, microbial activity, and the filtering capacity of vegetation and soil. This design eliminates the need for mechanical aeration or sludge transport over long distances, thereby avoiding greenhouse gas emissions typically associated with conventional sludge treatment and disposal. Additionally, the slow and controlled stabilization process within STRBs significantly reduces odor emissions and contributes to improved air quality. By minimizing both direct and indirect emissions, STRBs promote climate neutrality and advance net-zero targets in wastewater infrastructure.

A key strength of STRBs lies in their compatibility with decentralized wastewater management strategies. These systems are particularly well-suited for small to medium-sized wastewater treatment plants, especially in rural or peri-urban areas. Their implementation allows for localized sludge processing, reducing the need for long-distance transport, external infrastructure, and centralized treatment capacity. This not only lowers emissions and operational costs, but also enhances the self-sufficiency and resilience of local communities. The use of locally available materials, such as native plants and soils, further embeds STRBs within regional ecological and social contexts. As such, they exemplify a decentralized, low-emission, and place-based approach to circular economy implementation.

Sludge Treatment Reed Beds represent a multifunctional solution that integrates CE principles into wastewater management practice. Through nutrient recovery, energy efficiency, and local processing capacity, STRBs reduce environmental burdens while closing material loops and supporting sustainable regional development. Their broader adoption may significantly contribute to more circular, low-impact sanitation systems and the transformation of wastewater infrastructure into regenerative systems.

CONCLUSIONS

This study critically evaluated the performance of STRB systems in relation to sludge quality, ES delivery, and CE integration, with particular attention to the influence of operational conditions. The findings highlight the multifunctionality and regulatory relevance of STRBs as nature-based infrastructure for sustainable sludge management.

- Operational parameters, especially system age and resting period, significantly influence the

quality of sludge treated in STRBs. Longer idle times correlate with improved dewatering and mineralization, resulting in higher DM and lower OM.
- Nutrient concentrations in the STRB-treated sludge, particularly TP and TKN, are within or exceed the EU-defined thresholds for organic fertilizers, confirming their agronomic potential and contributing to nutrient cycling in accordance with circular economy objectives.
- Metal concentrations in all analyzed samples remained below legal limits for agricultural application, validating STRBs as a safe and compliant sludge management technology.
- STRBs provide multiple ES, including provisioning (biomass and nutrients), regulating (waste degradation, climate mitigation), and cultural (aesthetic and educational value). These align with the CICES framework and underline the multifunctionality of STRBs.
- CE contributions of STRBs include low-energy operation, emissions reduction, and local resource use. Their suitability for decentralized wastewater management makes them particularly relevant in rural and peri-urban areas.
- Implementation challenges, notably the need for large land areas, delayed full-scale operation, and lack of local expertise, remain barriers to broader STRB adoption, especially in Poland. Capacity-building and design standardization are critical to unlocking their full potential.

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