

A review of sewage sludge treatment and management methods in wastewater treatment plants

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ABSTRACT

The purpose of this paper was to review the methods of sewage sludge treatment and management in wastewater treatment plants with particular emphasis on constructed wetland systems as nature-based solutions (NBS). Sewage sludge management is one of the major challenges associated with wastewater treatment due to the high associated costs of sludge processing, transport, and disposal, as well as the increasing environmental requirements concerning its safe utilization and overall carbon footprint. This review presented the current state of knowledge on sewage sludge treatment and management, with particular emphasis on technologies suitable for small and decentralized wastewater treatment plants. Conventional methods, including thickening, mechanical dewatering, anaerobic and aerobic stabilization, composting, chemical stabilization, thermal drying, incineration, pyrolysis, and gasification, were discussed in terms of their technological characteristics, environmental impacts, energy requirements, and applicability. Attention was given to NBS, especially Sludge Treatment Reed Beds (STRB), which enable simultaneous dewatering, drying, and partial stabilization of sludge through filtration, gravity drainage, evapotranspiration, and biological processes. The literature indicated that STRB can significantly reduce sludge volume while requiring relatively low energy inputs and limited-to-zero chemical addition. These characteristics make this technology particularly promising for small and decentralized wastewater treatment plants, where conventional sludge treatment technologies are often economically and technically difficult to implement. The effectiveness of STRB depends mainly on the sludge loading rate, feeding frequency, resting periods, filter media properties, vegetation development, and climatic conditions. Despite their advantages, limitations related to land requirements, long treatment periods, seasonal variability, and the risk of clogging must be considered. The review highlighted the potential of STRB as a low-energy and environmentally sustainable approach to local sewage sludge management and identified the need for further research on design parameters adapted to temperate climates and decentralized wastewater treatment systems.

Keywords: dewatering, stabilization, sewage sludge, constructed wetlands, circular economy, nature-based solutions, Polesie National Park.

INTRODUCTION

One of the greatest problems encountered during wastewater treatment is the generation of waste (screenings, sand) and sewage

sludge, which requires management. According to Kacprzak et al. (2017), the average cost of disposing of 1 ton of dry sewage sludge in Europe ranges from €160 to €310, varying depending on the country and the available sludge

recovery or disposal methods. Consequently, sewage sludge disposal costs are significant, typically accounting for 20 to 65% of the operating costs of a wastewater treatment plant (Ragazzi et al., 2015).

In recent years, increasing attention has been paid to aspects of sewage sludge management, from both an economic and environmental perspectives. Currently, a growing number of research and implementation projects are being conducted to develop cost-effective sewage sludge management technologies that will enable its reuse, for example, in agriculture or for energy purposes (Ferrentino et al., 2023; Đurđević, 2022; Mazur-Wierzbicka et al., 2021). Such technologies allow for closing the circulation of matter in the natural environment, which is currently one of the main elements of the Circular Economy (CE) concept promoted by the European Union (von Kolpinski and Kratzer, 2024).

In conventional collective activated sludge wastewater treatment plants, the first type of sludge is generated during mechanical wastewater treatment in primary settling tanks, followed by excess sludge collected in the secondary settling tank. Both types of sludge have distinct physicochemical properties, which determine the selection of appropriate dewatering and stabilization methods (Królik et al., 2019).

The primary legal acts related to sewage sludge management in Poland are: the Act of December 14th, 2012, on Waste, the Regulation of the Minister of the Environment of February 6th, 2015, on Municipal Sewage Sludge, and the Regulation of the Minister of Economy of July 16th, 2015, on the Acceptance of Waste for Landfilling. These provisions result from European Union legal acts: 1) Council Directive 86/278/EEC of June 12th 1986 on the protection of the environment, and in particular of the soil when sewage sludge is used in agriculture, 2) Directive 2008/98/EC of the European Parliament and of the Council of November 19th 2008 on waste and repealing certain Directives, 3) Council Directive 1999/31/EC of April 26th 1999 on the landfill of waste. Other legal acts related to sewage sludge management include: the Regulation of the Minister of the Environment of January 20th 2015 on the R10 recovery process, the Regulation of the Minister of the Environment of May 15th 2015 on the recovery of waste outside installations and devices and the Act of July 10th 2007 on fertilizers and fertilization, the Regulation of

the Minister of Development of January 21st 2016 on the requirements for the thermal treatment of waste and methods of handling waste generated as a result of this process.

The operation of small, domestic wastewater treatment plants is also associated with the production of sewage sludge. The type of sewage sludge produced in domestic wastewater treatment plants depends on the treatment technology used. Activated sludge or biofilter treatment plants, similar to collective treatment plants, produce both primary sludge collected in a primary settling tank and excess sludge separated in a secondary settling tank. However, constructed wetland treatment plants, percolation drainage systems, or sand filters produce only primary sludge.

Domestic wastewater treatment plants are built in areas with scattered development, where the construction of sewer systems and collective wastewater treatment plants is economically unjustified. Statistical data show that the number of domestic wastewater treatment plants in Poland is constantly growing, with over 477,000 operating in 2024 (CSO 2025). The increasing number of domestic treatment plants is producing more sewage sludge, which requires appropriate management. Most often, this sludge is transported to collective sewage treatment plants for dewatering and disposal, which generates very high costs. Collective sewage treatment plants are usually not designed to treat and dewater sludge from domestic sewage treatment plants, which are characterized by high pollutant loads. This leads to operational problems. Therefore, many collective treatment plants accept only a maximum of 10% of the sewage and sludge delivered compared to that received through the sewer system.

Currently, few studies present the technologies for dewatering and stabilizing small amounts of sewage sludge generated in small wastewater treatment plants, especially in domestic wastewater treatment plants. Therefore, the aim of this review article was to present various methods of sewage sludge disposal, with particular emphasis on artificial constructed wetlands, which are considered nature-based solutions (NBS).

SEWAGE SLUDGE PROCESSING

The goals and objectives of sewage sludge treatment have remained unchanged for many years (Turovskiy et al., 2006; Wang et al., 2008;

Boruszko, 2001). Sewage sludge treatment aims to reduce the harmful environmental impact of sludge (Danso-Boateng, 2017; Vouk et al., 2022). Management of the sewage sludge treatment process directly affects the effectiveness of sludge disposal and the possibilities of its further use. Currently, additional challenges in the sludge treatment process include limiting the spread of microplastics (Khan et al., 2026), carbon dioxide emissions (Diannan et al., 2025), heavy metals, and pharmaceuticals (Tarpani, 2020). Sludge treatment is a key process in wastewater treatment plants, aimed at neutralizing and hygienizing sludge. Treatment processes should ensure safety during transport and subsequent storage of sludge. To achieve this, the stabilization process must reduce sludge volume, halt natural fermentation, and eliminate pathogens (Neyens et al., 2003). Sewage sludge treatment processes should be efficient, economically advantageous, and sustainable. Responsible handling of sewage sludge should be consistent with evolving environmental protection requirements (Turlej, 2026; KołECKA, 2017a), and the treated sludge should be ready

for disposal. Conventional sewage sludge treatment technologies, known as primary treatment, are typically performed within wastewater treatment plants. Primary treatment involves a series of successive processes: thickening, stabilization, dewatering, and hygienization (Trojanowska et al., 2012; Worwąg et al., 2022; KołECKA 2017a; KołECKA, 2017b; Środa et al., 2012). The development of sewage sludge treatment technologies is currently based on improving primary processes to optimize sewage sludge management. In the situations requiring further action, sewage sludge is subjected to more advanced secondary treatment processes involving drying and incineration (Worwąg et al., 2022; KołECKA, 2017b; Środa et al., 2012; Pietrzak et al., 2022). Figure 1 shows conventional sewage sludge management technologies divided into individual stages and processing processes.

The above-mentioned sewage sludge management technologies (Figure 1) are used primarily in large collective wastewater treatment plants. For economic reasons, their use in domestic treatment plants is usually unjustified.

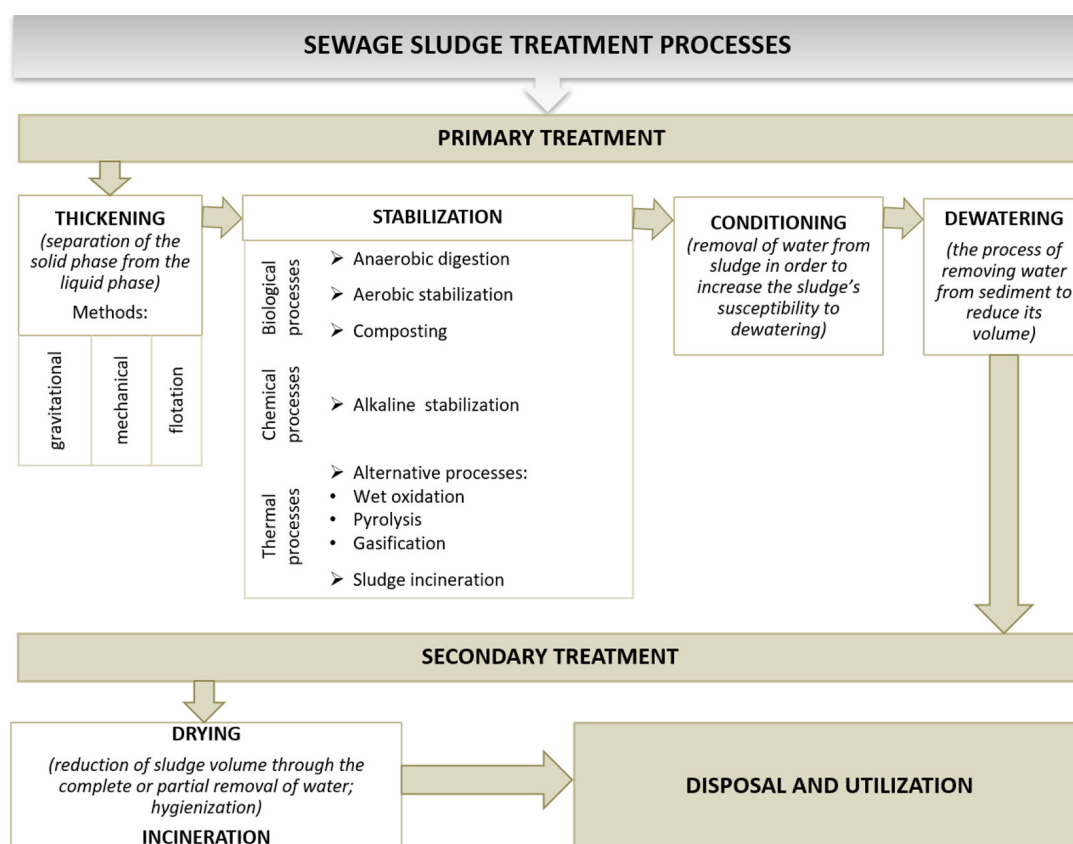


Figure 1. Conventional sewage sludge management technologies divided into individual stages and processing processes – authors' own study based on (Worwąg et al., 2022; KołECKA, 2017a; Środa et al., 2012; Pietrzak et al., 2022)

CHARACTERISTICS OF SEWAGE SLUDGE STABILIZATION TECHNOLOGY

Thickening and dewatering

The costs of all sludge disposal technologies are strongly dependent on the sludge volume, water content, and type and concentration of solids. Removing water from sewage sludge is a key operational element of wastewater treatment plants and has significant economic implications, as it is associated with the costs of thickening, transport, and disposal (Miodonski et al., 2025). Sludge treatment and disposal can account for up to 60% of the total operating costs of a wastewater treatment plant (Liu et al., 2016).

In the first phase, sludge generated in a wastewater treatment plant must be subjected to thickening processes. Thickening is intended to remove some free water and increase the dry solids concentration in the sludge. Reducing the sludge volume facilitates transport and further processing (Jara et al., 2026).

Sludge thickening can be accomplished using gravity, mechanical, and flotation methods with the addition of polyelectrolytes. The choice of a specific method depends on the type of sludge, economic considerations, and end requirements. Gravity thickening involves the sedimentation of particles denser than water. It is accomplished by filling the thickener tank and periodically draining the supernatant liquid or using continuous mechanical mixing, which significantly shortens the process. Mechanical thickening requires an additional force to aid in the separation of individual phases, in the form of centrifugal force or pressure changes. Centrifugal force is used in sedimentation centrifuges, where the efficiency of these devices depends on the device parameters, the sludge inflow rate, the layer thickness, and the thickening aids used. Flotation thickening utilizes the phenomenon of flotation. Flotation can occur biologically (gas particles are released from the sludge during thickening), chemically (through the addition of chemicals), and by introducing air into the sludge. In the flotation process, microparticles of air produced adhere to solid particles (pollutants) and float to the surface (Yang et al., 2025).

To enhance thickening, process-enhancing agents are used. Conditioning sewage sludge aims to increase the efficiency of thickening and dewatering and reduce processing costs. The goal

of sewage sludge conditioning is to transform the physicochemically and physically bound water into water free of surface tension, which is easiest to remove from the sludge (Kowalczyk, 2024; Zhang et al., 2024). The sludge dewatering process is aided by additional agents. Research is underway to enable the use of readily available, biodegradable, and non-toxic compounds that reduce iron compounds through the addition of perlite and cellulose (Kamizela et al., 2024). The addition of wood chips also positively impacts dewatering quality (Rabea et al., 2026).

Sludge dewatering can be performed mechanically in centrifuges, presses, and filters. Belt presses are frequently used in Poland, where sludge is forced between two porous filter belts. The pressure exerted by the belts is gradually increasing, effectively removing water. Compared to ring and chamber presses, lamella centrifuges, and conventional centrifuges, they are, in most cases, the least efficient (Wilinski et al., 2014). Mechanical dewatering is necessary when large volumes of sludge need to be processed in a short time. This requires specialized equipment and increasingly advanced technologies.

Sludge dewatering can also be achieved naturally, utilizing natural filtration and evaporation processes. This is performed in sludge plots or lagoons. This process is quite lengthy and requires additional steps to improve evaporation from the surface of the poured sewage sludge (Kolecka et al., 2018). The use of natural sludge dewatering in filter beds is feasible in domestic wastewater treatment plants where the amount of sludge produced is small. This method is relatively inexpensive and does not require specialized equipment.

Sludge thickening and dewatering are used in every treatment plant and affect further processing.

Anaerobic and aerobic stabilization of sludge

Sludge stabilization is another essential process in sewage sludge treatment. It improves both operational safety and economic efficiency. It enables sludge volume reduction, sanitization, and the recovery of valuable resources such as biogas or phosphorus. Selecting a stabilization process that considers sludge composition, operational requirements, and legal regulations is crucial for efficient and sustainable sludge treatment.

Sludge stabilization processes can be divided into three groups: biological, chemical, and

thermal. The choice of process depends on many factors: sludge composition, plant size, disposal objectives, and process costs. Biological sewage sludge stabilization leverages the activity of microorganisms to degrade sludge (Figure 1). For this purpose, it utilizes organisms available in anaerobic and aerobic processes.

In the process of anaerobic methane fermentation, microorganisms break down complex organic molecules into simpler compounds, producing gases (CO_2 , H_2) and volatile fatty acids, which are then converted into methane (CH_4) and carbon dioxide (CO_2). The process is carried out in sealed tanks. Increasing the efficiency of the process involves adding enzymes, such as cellulose or lipase (Grobelak et al., 2025). The process of stabilizing sewage sludge during fermentation is inextricably linked to methane production. Supporting this process by adding enzymes allows for the transformation of complex compounds into simpler ones, facilitating removal or conversion into the desired biogas (Grobelak et al., 2025). The methane fermentation process reduces the total carbon content (Cieřlik et al., 2015). The use of conditioning agents can ensure high dewatering efficiency, but the order in which coagulants and flocculants are added is also important (Bartkowska, 2017). Pre-stabilization of sewage sludge with CaO significantly reduces fecal bacteria and viruses (Wang et al., 2025). Methane fermentation technology can process high-moisture sludge, produce methane-rich biogas, and generate heat and electricity, which is extremely important for energy recovery from sewage sludge (Oladejo et al., 2019). However, the process is lengthy, low-yielding, and high-cost, and persistent organic pollutants and heavy metals remain in the sludge (Oladejo et al., 2019).

The opposite of methane fermentation is the aerobic stabilization of sewage sludge and composting. These methods involve supplying oxygen to organic matter. The choice of a biological method or the use of both methods simultaneously depends on available substrates, technical capabilities, and legal and environmental conditions. Aerobic stabilization is carried out in open chambers using oxygen contained in the air (Popenda et al., 2019). To make the stabilization process more efficient, high-purity oxygen is added (Boruszko et al., 2026; Bartkowska et al., 2022), and the effect of oxygen content on sludge volume reduction is also determined (Bartkowska et al., 2022). Microorganisms oxidize organic compounds to simple,

stable compounds: water, carbon dioxide, nitrates, and sulfates. Sludge stabilized in this way is more difficult to dewater. The process of aerobic sludge stabilization is the starting point for other processes based on its foundations (Chiarello et al., 2024). Aerobic stabilization is more cost-effective for medium and small wastewater treatment plants (Liu et al., 2012).

Composting

A recognized method for stabilizing sewage sludge is composting. Composting utilizes microorganisms to break down the organic matter in sewage sludge through aerobic decomposition into fertilizer (Wang et al., 2025). This process has numerous limitations, including inefficient oxygen transfer, uneven aeration, high gas emissions, and insufficient control of emerging pollutants (Nguyen and Shima, 2019). Composting efficiency is influenced by temperature, humidity, aeration, the carbon-to-nitrogen (C:N) ratio (Chiarello et al., 2025), and the addition of other process-enhancing agents. Alternative technologies improving compost quality are based on co-composting (Chiarello et al., 2025; Wang et al., 2025; Amini et al., 2025), intravascular systems (Amini et al., 2025), vermicomposting (Kumar et al., 2024; Rusănescu et al., 2022), and various pretreatment methods by adding CaO (Pirsaheb et al., 2026; Amini et al., 2025). Research on aeration and the reduction of anaerobic zones was conducted by Nguyen and Shima (2019). According to these authors, the total mass of plants produced using composts was comparable to that of plants produced using artificial fertilizers.

Composting with biochar has been shown to positively affect nitrogen retention and heavy metal mobility in compost (Qin et al., 2023). Studies indicate a positive impact on pollutant reduction in compost produced with biochar (Amini et al., 2025; Du et al., 2019). It has been found that composting sewage sludge is possible at home. Studies on composting sewage sludge using wood chips and grass, materials produced at home, indicate a negative impact of grass addition on the composting process and a positive effect on effective heavy metal reduction (Chamrádová et al., 2025). The method is relatively simple and not energy-intensive. However, it requires significant user attention to ensure appropriate conditions for the process to proceed optimally over the long term.

Chemical stabilization

Chemical stabilization of sewage sludge is most often performed using CaO and is usually applied in emergency situations. Liming, in its simplest form, can be performed manually using existing infrastructure. However, to ensure repeatability, safety, and increased efficiency, automatic processing lines are used to dose and mix lime with sewage sludge. Stabilization with quicklime ensures microbiological safety, minimizes the risk of environmental pollution, and increases the potential for sludge reuse (Pirsaheb et al., 2026). Lime stabilization quickly raises pH, improves dewaterability and odor control, and immobilizes heavy metals, making it a technically simple and cost-effective method for small and medium-sized wastewater treatment plants (Zhang et al., 2024). The use of chemically stabilized (lime) sludge positively impacts soil properties (da Silva et al., 2026). The process of lime stabilization provides chemical and thermal energy needed to evaporate moisture from the sludge (Valderrama et al., 2013). Lime-stabilized sewage sludge can be used as a raw material for cement production (Valderrama et al., 2012).

Thermal stabilization

The content of over 50% organic matter in sewage sludge (Delibacak et al., 2020) provides a basis for utilizing the potential of sludge for energy conversion (Fonts et al., 2012). Thermal treatment, depending on the temperature, can lead to sludge thickening or even the conversion of all organic matter into inorganic compounds (Cieřlik et al., 2014). Based on research by Bartkowska et al. (2022), thermal sludge stabilization was found to be the most expensive solution. Despite this, the costs of thermal technologies are still significantly higher than those of other technologies (Oladejo et al., 2019). Incineration is commonly used in sewage sludge management, it was previously intended not for energy recovery, but for reducing waste volume and destroying harmful substances (Fonts et al., 2012; Oladejo et al., 2019). Incineration reduces waste mass and thermally decomposes pathogens and toxic organic compounds. This stabilization method eliminates significant problems associated with sewage sludge, such as unpleasant odors and storage space (Fytili et al., 2008).

At the same time, it can release a number of pollutants into the atmosphere and soil. Among the various methods of thermal sludge stabilization, incineration allows for the utilization of the energy stored in the sludge. To reduce sludge production and minimize negative environmental impacts, the incineration process should be optimized (Cieřlik et al., 2015). The sludge incineration process directly impacts the climate and is therefore continually being developed and improved (Oladejo et al., 2019).

Sewage Sludge Thermal Treatment Plants (STPs) implemented in recent years utilize the solutions that enable rapid and relatively safe sewage sludge disposal. This technology utilizes the combustion of semi-dried sewage sludge, eliminating the need for additional fuel. The resulting steam in a turbine generator is converted into thermal and electrical energy for use within the plant. Odor-laden air is burned in furnaces, ensuring the process is environmentally friendly (Warsaw Municipal Water and Sewage Company S.A. 2026). Sewage sludge is a renewable energy source that can provide carbon and hydrogen compounds. Therefore, pyrolysis, an alternative treatment for sewage sludge, could be an interesting solution for obtaining valuable chemical products (Fonts et al., 2012). The pyrolysis process takes place in an anaerobic environment at high temperatures. This process can produce up to 50% heterogeneous liquid. Some phases of this liquid have high calorific values, similar to petroleum-derived fuels (Fonts et al., 2012). Pyrolysis can process both raw and digested sludge. All resulting products can be utilized (Oladejo et al., 2019). Pyrolysis requires pretreatment of sludge by dewatering, and the process itself is complex compared to combustion, generating high costs for the entire process (Oladejo et al., 2019). Depending on the pyrolysis conditions, various end products can be obtained (Figueiredo et al., 2018; Raza et al., 2021; Rasaq et al., 2021).

Sewage sludge gasification is a stabilization application that allows for the processing of various substrates. Gasification eliminates emissions of SO_x, NO_x, fly ash, and characteristic metals. The gasification process ensures energy extraction and self-sufficiency (Oladejo et al., 2019). This process requires dewatering and drying the sludge, which creates the pathway for its formation, and the resulting syngas requires purification (Oladejo et al., 2019). The gasification

process takes place in a low-access environment, where pyrolysis, oxidation, and reduction processes occur. Otherwise, syngas, an environmentally safe slag, is produced, unlike the ash from sludge incineration.

Drying of sludge

Sludge drying aims to partially or completely remove water, reduce sludge volume, improve calorific value, and stabilize and sanitize it (Środa et al., 2012). To obtain sludge with moisture below 40%, drying is necessary. The greatest advantage of drying sludge in dryers is the short process time. Unfortunately, this process is very energy-intensive, and the cost of building a technological line is very high (Środa et al., 2012). The high energy costs of drying have led to attempts to use solar energy for this process. Research by An-nori et al. (2022) on the use of solar drying demonstrated high effectiveness in reducing sludge volume and pathogens, and the drying itself did not reduce the agronomic value of the dried sludge. Another low-emission drying method was the use of heat pumps. This method achieves temperatures

below 70 °C. Therefore, the research on the effects of temperature, air velocity, and conditioning additives (e.g., CaO, sawdust) on improving drying efficiency at low temperatures is ongoing (Zhang et al., 2024; Zou et al., 2022).

Sludge moisture levels often remain high after standard dewatering methods, preventing effective energy recovery during incineration process. As a result, after dewatering, sludge must be thermally dried (Kobayashi et al., 2020). Thermal drying of wet sludge using combustion exhaust gases is an effective method. This allows for the recovery of as much residual heat as possible from the exhaust gases and significantly reduces sludge dewatering costs (Yang et al., 2016). Integrating heat recovery from the complete incineration of organic matter for heating or electricity generation reduces wastewater treatment plant operating costs (Yang et al., 2016).

All sewage sludge stabilization methods, with high operating and maintenance costs, are economically applied to large products (Oladejo et al., 2019), which makes them practically unsuitable for applications in small sewage treatment plants or household facilities.

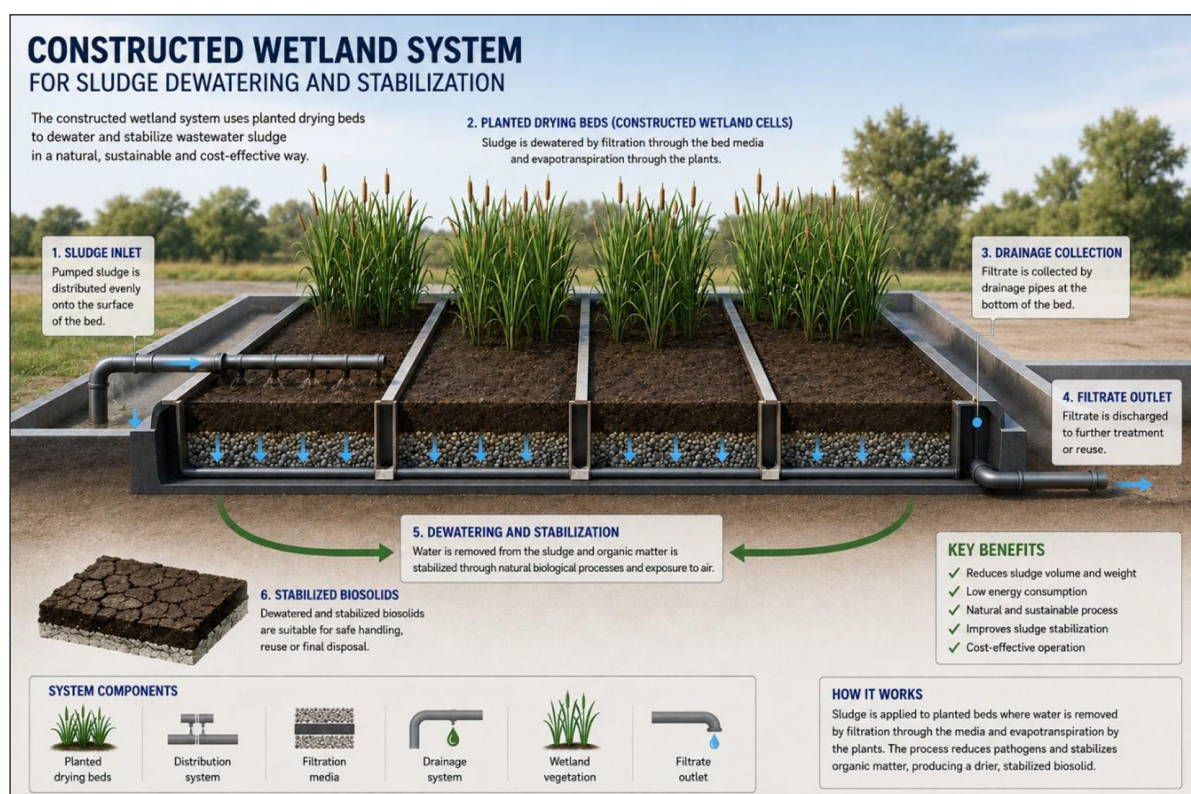


Figure 2. Example scheme of a constructed wetland system for dewatering and stabilizing sewage sludge (Author's own elaboration; graphical elements generated with the assistance of ChatGPT (OpenAI), 2026)

APPLICATION OF CONSTRUCTED WETLAND SYSTEMS FOR DEWATERING AND STABILIZING SEWAGE SLUDGE

Kołecka (2017; 2019; 2026) pointed out that conventional methods of sewage sludge dewatering and stabilization are costly and energy-intensive. This poses a significant problem, especially for municipalities with small collective wastewater treatment plants serving up to 2,000 residents or with individual treatment plants. These municipalities have very limited budgets that do not allow for the use of conventional methods of sewage sludge dewatering and stabilization. In this case, the constructed wetland method may be a very good solution (Figure 2).

Constructed wetland systems for sewage sludge dewatering and stabilization have been used in Europe since 1988 under the name Sludge Treatment Reed Beds (STRB) (Nielsen 2002), also known as Sludge Treatment Wetlands (Stefanakis et al., 2014). These systems utilize natural physical and biological processes to simultaneously dewater, dry, and partially stabilize sludge (Uggetti et al., 2010; Tan et al., 2024).

STRB systems typically consist of beds filled with various layers of filter material, equipped with a drainage system, and planted with common reed (*Phragmites australis*) (Nielsen, 2002; Peruzzi et al., 2009). Sludge is periodically fed to the bed surface, where the solid phase is retained, and water is gradually removed. Water drains away by gravity through the sludge layer and filter material, and is additionally removed by evaporation and plant transpiration. Systems are typically operated alternately, utilizing feeding and rest periods. The rest period allows for further sludge dewatering, aeration, and mineralization, as well as partial regeneration of the bed's hydraulic properties (Uggetti et al., 2010; Tan et al., 2024). Drainage in STRBs results from the interaction of several mechanisms, primarily gravity outflow, filtration, and evapotranspiration. Evapotranspiration is of particular importance, as its contribution to total water removal can be very high. Stefanakis and Tsihrintzis (2011), in a study of 11 pilot reed beds, found that evapotranspiration accounted for approximately 58–84% of total water losses. This means that the system's effectiveness depends not only on the bed design but also on vegetation development and atmospheric

conditions. Consequently, temperature, solar radiation, and precipitation can significantly impact process efficiency, especially in temperate climates (Stefanakis and Tsihrintzis, 2011; Gholipour et al., 2022).

Another important function of constructed wetlands is sludge stabilization. During months or even years of sludge retention in the bed, biological decomposition of some organic matter and its mineralization occur. Both microbial activity and the presence of plant root systems are important here. Roots and rhizomes influence the sludge structure, hydraulic properties, and oxygen conditions in the root zone. During periods of rest, the sludge surface dries and may crack, facilitating gas exchange and further biological processes (Uggetti et al., 2010; Tan et al., 2024). Pilot studies have shown that reed beds can not only significantly reduce sludge volume but also reduce organic matter content, confirming the mineralization processes (Stefanakis et al., 2011; Stefanakis and Tsihrintzis, 2012).

The effectiveness of STRB operation is primarily influenced by the dry matter load on the surface, the frequency of sludge dosing, the length of the bed rest periods, the properties of the filter material, vegetation development, and climatic conditions (Tan et al., 2024). The sludge loading rate (SLR) is particularly important, defining the amount of dry matter of sludge delivered per unit of bed surface area per year. A meta-analysis of 73 publications revealed significant differences in SLR values between climate zones. Average SLR loads were approximately $50 \text{ kg DM} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ in one of the analyzed temperate climate groups, approximately $70 \text{ kg DM} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ in the other, and approximately $101 \text{ kg DM} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$ in the tropical climate (Gholipour et al., 2022; Al-Rashdi et al., 2024; 2025). These results indicate that design parameters should be adjusted to local climatic conditions and sediment properties.

Experimental studies confirm the high effectiveness of STRB technology. In pilot studies, Stefanakis and Tsihrintzis (2012) achieved sludge volume reduction exceeding 95%, with final dry solids content in some variants reaching 50–64%. Results obtained in full-scale installations are more variable and depend on operating conditions. Nielsen and Larsen (2016), based on 28 years of experience with STRB, demonstrated that compared to mechanical dewatering methods, such as centrifuges or belt presses, they are characterized by low energy consumption and no

need for chemicals, while simultaneously reducing sludge volume. Under Danish conditions, dewatered sludge achieved approximately 20–40% dry solids, depending on sludge quality (Nielsen and Larsen 2016). Uggetti et al. (2009), analyzing three full-scale systems in Catalonia, confirmed the possibility of simultaneous dewatering and sludge stabilization under real operating conditions.

One of the main limitations of this technology is the risk of clogging, which is the gradual reduction of bed permeability due to sludge accumulation and the retention of fine particles (Stefanakis et al., 2014). Excessively high surface loading or too short rest periods can lead to deterioration of hydraulic properties and reduced dewatering efficiency (Tan et al., 2024). Another limitation are the relatively high space requirements and long process times compared to intensive mechanical methods. The efficiency of the systems is also strongly dependent on climate, which is particularly important in Poland, where significant seasonal variations in temperature and evapotranspiration intensity occur (Gholipour et al., 2022). Among the key advantages of STRB are its low energy consumption, limited operating requirements, and the ability to combine several technological processes – dewatering, drying, and stabilization – in a single system (Uggetti et al., 2009; Uggetti et al., 2010). Therefore, this technology may be particularly attractive for small and medium-sized wastewater treatment plants. However, the stabilization process should not be equated with full sanitization. The possibility of further use of the sludge requires an assessment of its physicochemical and microbiological properties, including the content of heavy metals and pathogenic organisms (Uggetti et al., 2009; Stefanakis and Tsihrintzis, 2012).

In summary, STRB constructed wetlands are an effective method for natural drainage and partial stabilization of sewage sludge. Their operation is based on the synergistic use of filtration, gravity outflow, evapotranspiration, and biological processes occurring in the sludge and root zone (Uggetti et al., 2010; Tan et al., 2024). However, the effectiveness of the technology depends on the appropriate load selection, sludge dosing method, duration of rest periods, and climatic conditions (Gholipour et al., 2022). Therefore, in Polish conditions, determining design parameters adapted to a temperate climate is particularly important. Further development of the technology should focus on optimizing operating parameters, modeling

dewatering and mineralization processes, and developing the solutions that reduce the risk of clogging (Tan et al., 2024). Research into the potential use of various plants in constructed wetland systems for dewatering and stabilizing sludge, as well as various filter materials, is also important.

CONCLUSIONS

This paper presented the most important technologies for sewage sludge treatment and management, with particular emphasis on solutions applicable to small and domestic wastewater treatment plants. Conventional methods of thickening, dewatering, biological and chemical stabilization, composting, and thermal technologies were discussed, highlighting their effectiveness, costs, energy consumption, and operational limitations. Particular attention was paid to constructed wetland systems such as Sludge Treatment Reed Beds, which enable simultaneous dewatering, drying, and partial stabilization of sludge with low energy consumption and limited use of chemicals.

A literature review indicated that STRBs can be an attractive alternative to intensive mechanical and thermal methods, particularly for small sludge volumes generated in domestic and small collective treatment plants. However, the effectiveness of these systems depends on the appropriate bed loading, sludge dosing frequency, duration of rest periods, filter material properties, vegetation development, and climatic conditions. The main limitations include the relatively large space requirements, long process times, seasonal variability in efficiency, and the risk of bed clogging.

The review indicated that STRB systems align with the principles of a circular economy and nature-based solutions and can be particularly useful for locally managing small amounts of sludge. Further research is needed on design parameters adapted to temperate climate conditions, optimizing the load and operation of the beds, selecting filter materials, and assessing the quality and potential for final management of the stabilized sludge.

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