Chapter

Sustainable Management and Reuse of Sludge from Membrane Bioreactor Systems: Opportunities for Agricultural Application

Iva Ćurić, Ivan Brandić, Luka Brezinščak and Davor Dolar

Abstract

This chapter deals with the treatment and management of sludge resulting from wastewater treatment using membrane bioreactor (MBR) technology. With the increase in world population and industrial activities, the demand for effective wastewater treatment has increased, generating significant amounts of sludge. Although MBR technology is more efficient in terms of effluent quality, it produces sludge with different rheological and morphological characteristics than conventional activated sludge. This chapter discusses various methods for treating MBR sludge, including stabilization, dewatering, and thermal treatment, which are essential for improving sludge quality and reducing disposal costs. It also examines the potential for the reuse of MBR sludge in agriculture, highlighting methods such as composting and pelletization as sustainable approaches. These methods not only mitigate environmental impacts but also contribute to a circular economy by converting waste into valuable resources. The chapter concludes by highlighting the importance of proper sludge treatment and management to ensure compliance with environmental regulations and to fully utilize the potential of MBR sludge as a resource.

Keywords: membrane bioreactor, fertilizer, soil container, agriculture, sludge

1. Introduction

According to forecasts, the world's population will continue to grow over the next 50–60 years, reaching an estimated peak of around 10.3 billion people by the mid-2080s, up from 8.2 billion in 2024 [1, 2]. As the population grows, the demand for water will also increase significantly. In addition, this population growth often leads to an increase in industrial activity as the need for more goods, services, and infrastructure increases. The expansion of industry to meet these demands increases resource consumption, particularly water consumption, and leads to greater challenges in wastewater treatment and management [3].

Currently, most wastewater treatment plants rely on a combination of primary, secondary, and tertiary treatment processes to effectively treat wastewater. The main objectives of primary treatment include the removal of coarse and fine particles by screening, filtration, etc. Secondary treatment consists of biological processes, including aerobic and anaerobic processes, which are very effective in removing organic compounds and nutrients. Tertiary treatment, the final stage, involves chemical processes to further purify the wastewater [4]. All of the above processes produce a form of waste, namely sludge. Fytili and Zabaniotou state that on average, about 90 g of sludge is produced per person per day [5].

Although biological technologies such as conventional activated sludge (CAS) are very efficient at removing pollutants, they produce the most sewage sludge compared to all previous wastewater treatment processes [6]. Sewage sludge is the residual byproduct of wastewater treatment, which results in the separation of liquids and solids. The liquid fraction is discharged into water bodies, while the solid fraction undergoes further treatment and is ultimately disposed of. In the European Union, the USA, and China, between 18 and 33 million tons of dry weight are produced annually [6].

In 1969, as part of the Dorr-Oliver research program, Smith et al. presented a membrane bioreactor (MBR) for the first time and demonstrated its advantages over CAS technology, which enables higher effluent quality. MBR technology combines CAS with membrane separation using microfiltration, ultrafiltration, or nanofiltration membranes [7]. This combination offers several significant advantages compared to CAS. Nearly complete separation of sludge from the effluent and lower sludge production due to a higher solids retention time (SRT), a longer hydraulic retention time (HRT), and a higher concentration of mixed liquor suspended solids (MLSS) [8]. CAS and MBR technologies are presented in **Figure 1**.

However, the first MBR versions had to contend with considerable problems, in particular frequent fouling of the membranes and required costly maintenance [7]. In addition, these early systems were associated with high energy consumption, which further increased operating costs. Over the years, the MBR configuration has changed

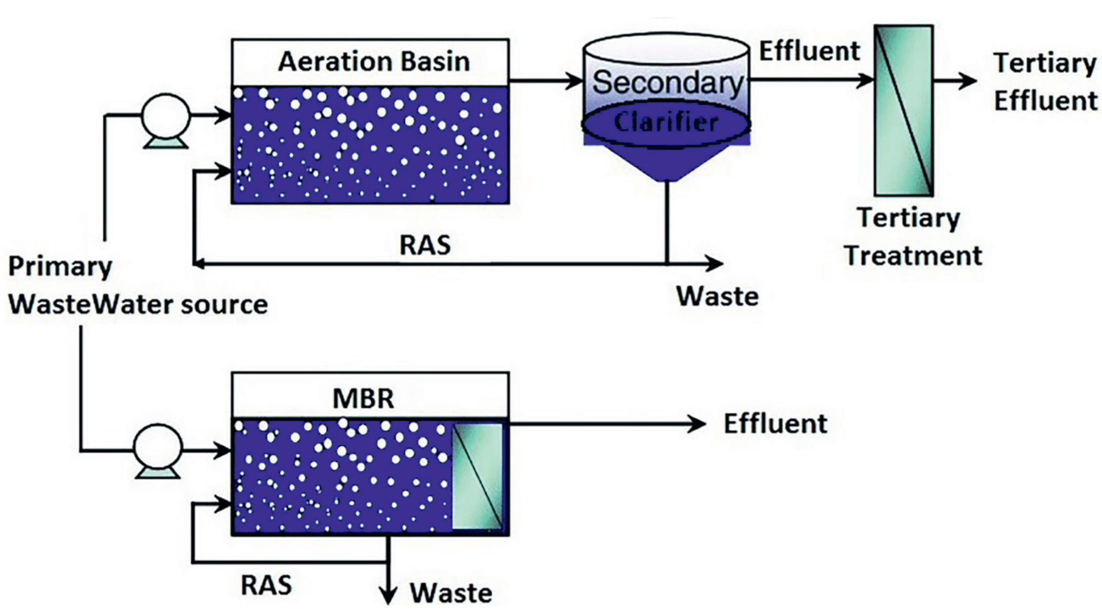

Figure 1.
MBR and CAS treatment of wastewater [9].

and overcome the abovementioned shortcomings. A clear indicator of the success and increasing acceptance of MBR technology is the global membrane bioreactor market, which was estimated at USD$ 3.35 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 7.0% from 2023 to 2030, highlighting the continuous improvement and wide acceptance of the technology [10].

Despite these advantages, both technologies generate sludge that has to be transported and treated. In Europe, however, the cost of sludge disposal can be as high as EUR 310 per ton, which can account for up to 65% of the total wastewater treatment costs [6]. One of the most popular methods of sludge treatment is incineration, which not only reduces the volume of sludge but also offers the possibility of generating thermal energy. However, this method has several significant disadvantages. Incineration requires a significant amount of energy to reach and maintain the high temperatures required for the process. It can also result in emissions of harmful gases such as CO_2, NO_x, and SO_x, which contribute to air pollution. The process also produces ash, which may contain heavy metals and other substances, requiring further treatment or disposal. Public acceptance can be a problem, as the process may meet with resistance due to potential environmental impacts and esthetic concerns. In addition, the high costs of technical cleaning and ash disposal add to the financial burden. Strict control measures are required to monitor and control pollutants and ensure compliance with environmental regulations [11].

Given these challenges, research into alternative approaches to sludge management is crucial. One such approach is the reuse of sludge, which not only mitigates some of the disadvantages associated with incineration but also offers economic benefits. Replacing conventional CAS technologies with MBR can also have a positive impact on sludge treatment. In addition, MBR sludge often has better dewatering characteristics and lower pathogen content compared to CAS sludge, making it easier and cheaper to process [12]. The Technical Report on End-of-Waste Criteria for Biodegradable Waste Subject to Biological Treatment classifies sewage sludge as a positive waste product, so that "clean" sewage sludge can be used as a fertilizer and is classified as a product and not as waste [13]. By reusing sewage sludge in this way, wastewater treatment plants can reduce their operating costs and even generate additional revenue. This approach is in line with the principles of the circular economy, where waste is transformed into valuable resources, contributing to both economic and environmental sustainability.

2. Characteristics of MBR sludge compared to CAS sludge

MBR sludge differs from CAS sludges not only quantitatively but also qualitatively, especially in terms of their rheology and morphology. These characteristics have a significant impact on system performance and the operating costs of the subsequent treatment process [14].

Sludge rheology includes viscosity, shear stress, shear rate, yield stress, and thixotropy. In contrast to CAS, MBR has a higher solids concentration, which has a major influence on sludge viscosity. The higher concentration of small flocs and the higher solids content in MBR sludge lead to higher viscosity. This makes the MBR sludge less flowable and makes effective circulation and mixing of the sludge more difficult. Mixing and circulating thick sludge requires a lot of energy. In addition, thick sludge contains much more water than CAS sludge, which also consumes more energy for the dewatering process, which is a kind of pretreatment before the actual sludge treatment [15]. Shear stress, shear rate, yield stress, and thixotropy describe the forces and behaviors required to initiate and maintain sludge movement, with the increased density of MBR sludge complicating these processes due to its greater resistance to flow and deformation. Pollice et al. [16] show in their study that with a higher concentration of suspended solids in the MBR, the energy required for mixing increases.

The sludge morphology describes the floc size, whereby the MBR flocs are less aggregated and therefore have a smaller particle size than in the conventional CAS system (**Figure 2**) [18]. Fenu et al. evaluated CAS and MBR sludge by microscopy. They found that the MBR flocs had open form and compact cores, cell clusters, filamentous bacteria, protozoa, metazoa, algae, and fungi. The particle size was 40–50 µm for the MBR and 200 µm for the CAS [19].

The microorganisms mentioned form a biofilm of extracellular polymeric substances (EPS). These substances play a key role in the aggregation of flocs in MBR sludge and contribute to the formation of dense and compact structures. In CAS sludge, this aggregation is less pronounced due to the lower EPS concentration. The EPS concentration is related to the SRT. A longer SRT in the MBR leads to a higher EPS concentration [20]. According to Pontoni et al. [12], CAS EPS consists mainly of proteins (57–61%), carbohydrates (28–29%), humic acids (6–7%), and uronic acids (4–8%). On the other hand, MBR sludge contains lower proportions of proteins (17–50%), carbohydrates (13–22%), humic acids (2–4%), and uronic acids (32–60%).

Overall, EPS affects the morphology of the sludge and has a significant impact on the stability of the sludge, the degradability of the substrate, and other hydrodynamic conditions.

In addition to the rheology and morphological properties of the sludge, it is necessary to know the chemical composition of the sludge before treatment and disposal. However, this depends on the type of water in question, that is, the source from which it originates. For example, if the wastewater comes from the metal industry, it is likely to have a high concentration of heavy metals. This information is important if the sludge can be disposed of in a landfill [5]. Without proper treatment, disposal of sludge has catastrophic consequences for the environment. Alonso Álvarez et al. conducted a study on the sequential extraction of metals (Al, Cd, Co, Cu, Cr, Fe, Mn, Hg, Mo, Ni, Pb, Ti, and Zn) from sludge samples collected from five different municipal activated sludge plants. The study found that Cd, Co, Mo, Ni, and Ti pose only a low toxic risk due to their low concentrations, while Cr, Cu, and Pb were present in higher concentrations, which requires further investigation to assess their potentially harmful effects on the biological processes in the sludge [21].

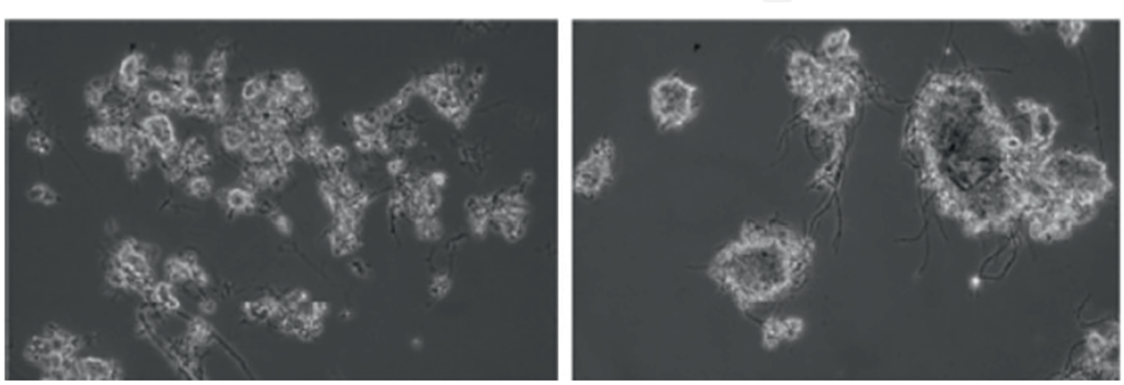

Figure 2.
CAS sludge flocs (left) and MBR sludge flocs (right) [17].

3. Treatment of the MBR sludge

Sludge treatment involves several steps, including thickening to reduce volume by removing water, stabilization to reduce organic content, odors, and pathogens, and dewatering and drying to further remove water and facilitate handling. Finally, testing for contaminants such as heavy metals and pathogens ensures that safety standards for land application are met. These steps are similar in both CAS and MBR, but there are some differences [22].

Stabilization is applied to both, but MBR sludge may require additional measures due to its different composition, especially the higher content of uronic acids. Dewatering and drying processes include dewatering and drying, although MBR sludge may be more difficult to dewater due to its higher EPS content. Safety testing is required for both application, but MBR sludge may have unique characteristics due to the different microbial activity in the system [12].

The dewatering process reduces the content of bound water, which consists of three types of water: interstitial, vicinal, and hydration water. Interstitial water is located in the spaces between the solid particles of the sludge and is relatively easy to remove. Vicinal water is bound to the surfaces of the sludge particles and is more difficult to remove than interstitial water. The hydration water is chemically bound to the sludge particles and is the most difficult to remove. Belt processes, centrifuges, and filter processes can press the water out of the MBR sludge [23]. The dewaterability process is very difficult due to the particle size of MBR sludge, but a longer SRT can solve this problem. D'Antonio and Napoli investigated the dewaterability of chromium-containing sludge from the tannery wastewater treatment plant. The experiment shows that the MBR sludge has a specific resistance to filtration (SRF) of 2.58×10^{11} m/kg and an SRT of 25 days. The results show better dewaterability, as MBR sludge contains more free water in this case [24].

Stabilization of MBR sludge is essential to improve its quality and handling. Methods include anaerobic and aerobic digestion and thermal stabilization [17].

Aerobic digestion of MBR sludge is a process in which microorganisms break down organic matter in the presence of oxygen. This process is extremely efficient in reducing sludge volume and eliminating pathogens. In aerobic digestion, microorganisms use dissolved oxygen to break down complex organic molecules, resulting in the release of carbon dioxide, water, and heat. The process is fast and produces a stable sludge with lower levels of pathogens. However, aerobic digestion is energy-intensive as it requires constant aeration, which can increase operating costs [25].

On the other hand, anaerobic digestion is a process of decomposition of organic material in the absence of oxygen. This process is slower compared to aerobic digestion but has the great advantage of producing biogas, a mixture of methane and carbon dioxide that can be used as a renewable energy source. In anaerobic digestion, microorganisms first hydrolyze complex organic matter into simpler molecules, which are then fermented into acids. Finally, methanogenic bacteria convert these acids into methane and carbon dioxide. This process is very effective in reducing sludge volume and generating energy but requires careful management as the methanogenic bacteria are sensitive to changes in environmental conditions, such as pH and temperature [17, 25].

In combination with MBR systems, anaerobic digestion can reduce the volume of sludge produced and at the same time generate biogas as an additional resource. Due to the long SRT in MBR systems, the resulting sludge usually has a high concentration of anaerobically degradable substances, which can increase the efficiency of anaerobic digestion. In addition, anaerobic digestion can help reduce the operating costs associated with sludge treatment while contributing to sustainability through the production of renewable energy [17].

Thermal stabilization of MBR sludge is a process in which the sludge produced in MBR systems is treated with heat and stabilized.

Due to the unique characteristics of MBR sludge, which often contains higher concentrations of biomass and EPS, thermal stabilization can help to degrade these complex materials more effectively. The main methods of thermal stabilization of MBR sludge include thermophilic aerobic digestion, thermal hydrolysis, and in some cases, incineration.

1. Thermophilic aerobic digestion

   In this process, the MBR sludge is treated at elevated temperatures (usually 45–70°C) under aerobic conditions. The higher temperatures accelerate the decomposition of the organic matter, which reduces the sludge volume more effectively and destroys pathogens. MBR sludge, which is already partially stabilized due to the long SRT, responds well to thermophilic conditions, resulting in faster stabilization and greater reduction of volatile solids.

2. Thermal hydrolysis

   Thermal hydrolysis can be particularly beneficial for MBR sludge. In this process, the sludge is exposed to high temperatures (usually 160–180°C) and pressures before anaerobic digestion. The intense conditions break down complex organic compounds and EPS, making the sludge more biodegradable. When MBR sludge is subjected to thermal hydrolysis, it is not only easier to anaerobically digest, but the subsequent digestion also produces more biogas, which contributes to energy production.

3. Incineration

   Although the incineration of MBR sludge is less common, it can still be used, especially if energy recovery is the main objective. Since MBR sludge has a high organic content, it can be effectively reduced to ash through incineration while recovering energy in the form of heat. However, due to the typically lower water content of MBR sludge compared to conventional sludge, pre-drying may be required to make incineration more efficient.

Thermal hydrolysis is an energy-intensive process that can significantly increase the carbon footprint of sludge management. While biogas production of biogas can offset some of these energy costs, the overall energy balance remains a concern, particularly for systems that rely heavily on nonrenewable energy sources [26]. Furthermore, while incineration can reduce sludge volume and generate thermal energy, it is also criticized for high energy requirements and the emission of harmful gases such as CO_2, NO_x, and SO_x. These emissions contribute to air pollution and climate change and require strict control measures and advanced technological solutions to mitigate their effects.

4. Agricultural benefit of MBR sludge

The conversion of MBR sludge into fertilizer or other useful products not only reduces disposal costs but also contributes to the circular economy and sustainable use of resources. MBR sludge usually contains significant amounts of organic matter, nitrogen, phosphorus, and trace elements such as potassium, calcium, magnesium, and sulfur. These substances are major components of most commercial fertilizers, making MBR sludge a potentially valuable source of nutrients for agricultural applications [27]. However, before application, the sludge must be treated as described in the previous section.

1. Composting of the MBR sludge

   Composting is one of the most widely used methods for converting stabilized MBR sludge into valuable fertilizer, mainly due to its compliance with the principles of green technology. Composting solves the problems associated with sludge through controlled aerobic fermentation, which effectively converts organic matter into stable humic compounds. This process not only reduces pathogens but also results in nutrient-rich humus, which is an excellent, high-quality organic fertilizer. In composting, stabilized sludge is usually mixed with organic materials such as sawdust, food waste, or agricultural residues to enhance the process. Effective aeration is crucial, but dewatered sludge often has low porosity. To improve aeration, a bulking agent, such as a carbonaceous material, is added and at least 20% of the mixture must be permeable to air. This controlled degradation, which is driven by various microorganisms and generates heat that can exceed 70°C, effectively destroying pathogenic germs and reducing the moisture content of the sludge through evaporation. Composting is most effective with fresh sludge rich in organic matter and nitrogen, but can also be used with digested or aerobically stabilized sludge. The process is naturally supported by the microflora present in the sludge or in the air, so no additional seed is required. The pH of the mixture is self-regulating between 6.5 and 8, making composting a robust method even for sludge produced from physical-chemical treatments. Due to its effectiveness and consistency with sustainable development goals, composting has become an increasingly popular solution for the management and reuse of sludge in recent years [28, 29].

2. Pelletization of MBR sludge

   MBR sludge pelletization is a process that transforms stabilized sludge into a more manageable form so it is easier to handle, transport, and use in agriculture or other industries. This method involves several important steps, each of which contributes to the formation of small, solid pellets that are rich in nutrients [30]. The pelletization process includes several processes:

   a. Preparation and drying:

      In the first phase of pelletization, the moisture content of the sludge is reduced. Drying is crucial, as a high moisture content can hinder the pelletization process and affect the quality of the final product. Drying can be carried out by thermal methods or by natural drying, depending on the available resources and the specific requirements of the process [31].

b. Grinding and homogenization

After drying, the sludge is ground to achieve a uniform consistency. This step is important to ensure that the sludge is pelletized evenly, resulting in pellets of uniform size and density. Homogenization also allows the sludge to be effectively mixed with additional materials, such as binding agents, which can be added to improve the properties of the pellets [32].

c. Pelletization

The ground and dried sludge is then fed into a pellet mill, where it is compressed into solid, cylindrical pellets. In the pellet mill, the sludge is formed into pellets under pressure and heat, which are then cooled to maintain their shape and structure. Sometimes, binding agents are added during this process to improve the strength and durability of the pellets [31].

d. Cooling and packaging

Once the pellets are formed, they must be cooled before they can be stored or transported. Cooling prevents the pellets from breaking apart and ensures that they retain their structural integrity. Once cooled, the pellets are packaged in bags or other suitable containers so they can be distributed and used [7].

3. Direct application into the field as a soil conditioner

A soil conditioner, also known as a soil amendment or improver, is a substance that is added to soil to improve its physical properties, such as its structure, porosity, and water retention capacity. Soil conditioners aim to improve the overall health and productivity of the soil by modifying its physical qualities [33].

The use of MBR sludge as a soil conditioner involves several steps that contribute to improving soil quality:

a. Preparation and drying of sludge

First, the MBR sludge must be properly treated and dried. Drying is crucial as it reduces the moisture content of the sludge, improves its stability, and facilitates its handling.

b. Application of sludge to soil

The dried sludge is spread evenly over the soil surface. The amount of sludge applied depends on the specific needs of the soil and the type of soil to be treated.

c. Incorporation into the soil

Once the sludge has been spread, it must be incorporated into the top layer of soil. This is usually done by plowing or tilling. This ensures that the sludge is well mixed with the existing soil, which helps to improve soil structure and increase porosity [34].

Overall, the incorporation of MBR sludge into the soil can significantly improve its physical properties, resulting in better soil structure, higher water retention capacity, and reduced soil erosion. The organic matter in MBR sludge binds soil particles together and creates a looser, more workable soil that supports vigorous root growth. In addition, the improved water retention is particularly beneficial for sandy or dry soils, while the improved structure prevents erosion and protects the topsoil. Although MBR sludge is not a fertilizer in the traditional sense, it contributes to soil fertility, which can ultimately lead to higher agricultural productivity.

5. General challenges in the reuse of MBR sludge

Despite the numerous benefits of MBR sludge reuse, such as improved dewatering properties and reduced pathogen content, significant problems remain. One of the main problems is the presence of emerging contaminants, such as pharmaceutical residues, personal care products, and microplastics, which are not always completely removed by conventional treatment processes. These substances can accumulate in the soil over time and pose a potential risk to human health, the environment, and long-term soil fertility. Heavy metal contamination also remains a key issue, as toxic metals can gradually accumulate when sewage sludge is applied to agricultural land, which could affect crop safety and quality [35].

The logistical challenges of transporting and spreading sewage sludge are also significant, especially when it comes to large-scale agricultural applications. The cost of sludge transportation can be prohibitive, especially in regions where agricultural land is far from wastewater treatment plants [36]. In addition, the varying composition of sludge depending on the source of the wastewater makes it difficult to apply uniformly. MBR sludge in particular can have significant differences in nutrient and pollutant content, which requires careful monitoring and testing before it can be safely reused.

Another challenge is the legal framework for the reuse of sewage sludge. While some regions have established guidelines for the safe use of treated sewage sludge in agriculture, in other regions there are no clear regulations, leading to uncertainty and hesitation among potential users. Even in regions with strict standards, it can be a lengthy and costly process for wastewater treatment plants to obtain the necessary permits and certifications [37]. Public perception also plays an important role, as the reuse of sludge in agriculture is often viewed with skepticism. Concerns about unpleasant odors, contamination, and the possibility of pathogens or chemicals entering the food chain can lead to resistance from farmers and consumers alike. To overcome these concerns, extensive awareness campaigns and transparent communication about the safety measures involved in sludge treatment are needed.

Finally, the long-term effects of MBR sludge application on soil health are not yet fully known. While the short-term benefits of organic matter, nitrogen and phosphorus enrichment are obvious, the cumulative effects of repeated sludge applications need to be further investigated. Problems such as soil compaction, changes in microbial communities and nutrient imbalances could occur over time, so continued research is needed to ensure that the practice remains sustainable in the long term.

6. Possible future innovative sludge treatment methods

Current research is exploring a range of advanced technologies aimed at improving the efficiency of sludge treatment and reducing the environmental impact. For example, advanced oxidation processes are being investigated for their ability to degrade persistent organic pollutants and microplastics that are difficult to remove using conventional methods [38]. Hydrodynamic cavitation is another promising technique that supports sludge degradation, reduces particle size, and improves stabilization. This process, which is suitable for both anaerobic and aerobic digestion systems, facilitates the handling and reuse of sewage sludge. The process of stabilizing sewage sludge with materials such as clay minerals and biochar provides an effective way to reduce microbial activity, manage heavy metals, and optimize nutrient recycling. Studies suggest that this method can be used to produce a safe soil amendment and fertilizer that is an environmentally friendly option for agriculture [39].

Another promising area of innovation is the integration of artificial intelligence (AI) and machine learning to optimize sludge treatment processes. AI-driven systems can analyze large data sets to predict and adjust energy consumption, chemical dosing, and system parameters in real-time, leading to a significant reduction in energy consumption and operating costs [40]. In addition, waste-to-energy technologies continue to evolve, with research focusing on maximizing biogas production through anaerobic digestion or exploring pyrolysis and gasification as alternatives to conventional incineration [41]. These processes not only reduce the volume of sludge but also convert it into syngas, biochar, or other valuable by-products, further contributing to the circular economy.

7. Conclusion

The use of MBR sludge for agricultural reclamation offers a sustainable approach to wastewater treatment that is in line with the principles of the circular economy. As the world's population continues to grow, the demand for water and the need for efficient wastewater management is increasing. MBR technology offers several advantages over CAS technology, including better effluent quality and reduced sludge production. However, the treatment and disposal of MBR sludge remains a challenge due to its unique properties, such as higher viscosity and solids content, which require more energy for treatment.

By reusing MBR sludge as a resource for agricultural reclamation, we can address these challenges while contributing to sustainability. MBR sludge, which is rich in organic matter, nitrogen, phosphorus, and trace elements, has significant potential as a soil conditioner or fertilizer. Methods such as composting, palletization, and direct soil application turn this byproduct into a valuable resource for improving soil structure, fertility, and water retention. In addition, incorporating treated MBR sludge into agricultural practices reduces disposal costs, mitigates environmental impacts, and promotes the recovery of renewable resources through processes such as biogas production.

Thus, the reuse of MBR sludge not only improves the sustainability of wastewater treatment but also supports agricultural productivity and offers a holistic solution for resource management in an increasingly resource-constrained world.

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Conflict of interest

The authors declare no conflict of interest.

Notes/thanks/other declarations

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