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Dual-path exploration of anaerobic biotechnology under carbon neutrality goals: from wastewater methane production to systematic utilization of renewable energy

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This study investigates the application of anaerobic biotechnology in wastewater treatment and resource recovery within the carbon neutrality framework. It systematically elucidates the complete technological chain, from methane production to renewable energy utilization. In the context of intensifying global climate change, carbon neutrality has emerged as a critical strategic objective worldwide. The energy-intensive and high-carbon wastewater treatment sector has become a key focus for emission reduction. Distinct from conventional processes plagued by high energy consumption and carbon emissions, anaerobic biotechnology is garnering increasing attention due to its triple advantages in energy recovery, resource utilization, and emission reduction. By employing anaerobic microorganisms to convert organic matter into methane and other renewable energy sources, this technology not only reduces CO_2 emissions but also provides energy supplementation for wastewater treatment facilities. The research further examines specific applications of anaerobic biotechnology in methane synthesis, nutrient recovery from wastewater, and sludge treatment, along with synergistic mechanisms with other renewable energy technologies. While demonstrating significant potential, technology still confronts multifaceted challenges including process optimization, cost management, and social acceptance. Findings confirm that anaerobic biotechnology serves as a vital pathway for low-carbon transformation in wastewater treatment, offering multidimensional value for establishing circular economy systems and advancing sustainable development.

KEYWORDS

carbon neutral, anaerobic biotechnology, wastewater treatment, renewable energy, resource utilization

1 Introduction

The exacerbation of global climate change has made carbon neutrality a key strategic objective in several countries (Jin et al., 2021). Besides the reduction of greenhouse gas emissions, carbon neutrality requires the optimization of the energy mix and the sustainable use of resources (Springmann et al., 2018; Xu et al., 2024). The path to achieve carbon neutrality is complex and varied, involving not only the green transformation of the energy industry but also technological innovations in emission control and reduction in various high-emission industries (Abeydeera et al., 2019). Wastewater treatment, as a high-energy-consuming and high-emission industry, has become one of the key areas for reducing global emissions (Zhang et al., 2011; Górka et al., 2022). Efficient reduction of carbon emissions and achieving sustainable use of resources in the wastewater treatment process have become important issues that urgently need to be addressed (Xie et al., 2025; Zhao et al., 2021). While significant progress has been made in treating wastewater pollutants, conventional wastewater treatment processes are inherently energy intensive and produce large amounts of carbon dioxide and other greenhouse gases during the degradation of organic matter (Müller et al., 2022). Therefore, reducing emissions, reducing energy consumption and realizing resource recovery in the wastewater treatment process have become important issues in the context of carbon neutrality.

Among the wastewater treatment technologies, anaerobic digestion is one of the classic and evolving technologies with feasibility and reference, as well as its advantages. Wastewater treatment technology, as an advanced approach, is gaining attention from researchers and policymakers due to its potential advantages in energy recovery, resource utilization and emission reduction (He et al., 2017; Cheng et al., 2011; Plevri and Noutsopoulos, 2021). The core of anaerobic digestion technology lies in the utilization of anaerobic microbial communities for the degradation of organic matter and the generation of renewable energy sources such as methane through anaerobic digestion processes (Costanzo et al., 2021; Negri et al., 2020). Compared to traditional aerobic wastewater treatment technologies, anaerobic technologies can significantly reduce carbon dioxide emissions during the degradation of organic matter (Müller et al., 2022). Additionally, anaerobic technology can convert organic matter in wastewater into methane, reducing greenhouse gas emissions and providing a potential energy source for wastewater treatment plants, shifting the wastewater treatment process from energy consumption to energy production (Xu et al., 2024). This energy recovery and utilization align with the circular economy model advocated in the carbon-neutral strategy, which can effectively reduce the dependence on fossil energy in the wastewater treatment process.

This study is dedicated to the systematic investigation of the potential application of anaerobic technology in wastewater treatment and resource utilization and its environmental benefits. The second part of the paper focuses on the core aspects of the anaerobic digestion process, and analyzes its carbon neutralization pathway and carbon emission characteristics in depth; followed by a systematic overview of the mainstream anaerobic technologies in the third part of the paper, which lays the foundation for the subsequent analysis. Based on the clarification of the technical principles and carbon accounting methods, the study focuses on the specific strategies and effectiveness of anaerobic technologies for resource (e.g., energy and nutrient) recovery in wastewater treatment in Part IV, and explores their practice and potential as a renewable energy production pathway in Part V. The study also focuses on the carbon neutralization pathway and carbon emission characteristics of anaerobic digestion processes. By comparatively analyzing the significant carbon footprint of conventional treatment processes, this study aims to quantitatively reveal the unique carbon reduction advantages of anaerobic technology. Finally, the sixth section validates the effectiveness of the technology through a typical case study, while the seventh section rationally looks at the key challenges and directions for the future application of the technology.

2 Carbon neutralization and carbon emissions in anaerobic digestion of wastewater

2.1 Concepts and objectives of carbon neutrality

Carbon neutrality refers to the process of achieving net-zero carbon emissions by reducing carbon emissions and enhancing carbon sequestration. Rapid economic development and accelerated urbanization are not conducive to reducing carbon emissions. As a major agricultural country, China's agricultural development has significantly contributed to the national economy; however, it has also been accompanied by an increase in greenhouse gases, including carbon dioxide and methane (Xu et al., 2024; Liu et al., 2024). Therefore, reducing energy consumption intensity, adjusting the industrial structure, and improving the economic policy framework are essential strategies for promoting the development of China's low-carbon economy (Jin et al., 2021; Ma et al., 2019).

With advances in industrial energy technology, wastewater is no longer regarded as wastes; instead, many wastewater treatment plants now consider it a source of energy, nutrients, and clean water (Zhang et al., 2011; Fang et al., 2016; Wang et al., 2016). Achieving global carbon neutrality necessitates significant emission reductions across all sectors, and the wastewater treatment industry plays a crucial role in this effort due to its high energy consumption and substantial carbon emissions. The primary sources of carbon emissions from wastewater treatment plants mainly include microbial respiration and biogas combustion (Wang et al., 2016). The utilization of methane and carbon dioxide as energy sources in wastewater treatment through enhanced processes and the adoption of innovative technologies can significantly reduce greenhouse gas emissions and contribute to the global goals of carbon neutrality.

2.2 Carbon emission analysis of wastewater treatment processes in anaerobic technology

Anaerobic digestion is an energy-efficient option for reducing greenhouse gas emissions and recovering biofuels from waste materials. Greenhouse gas emissions from wastewater treatment

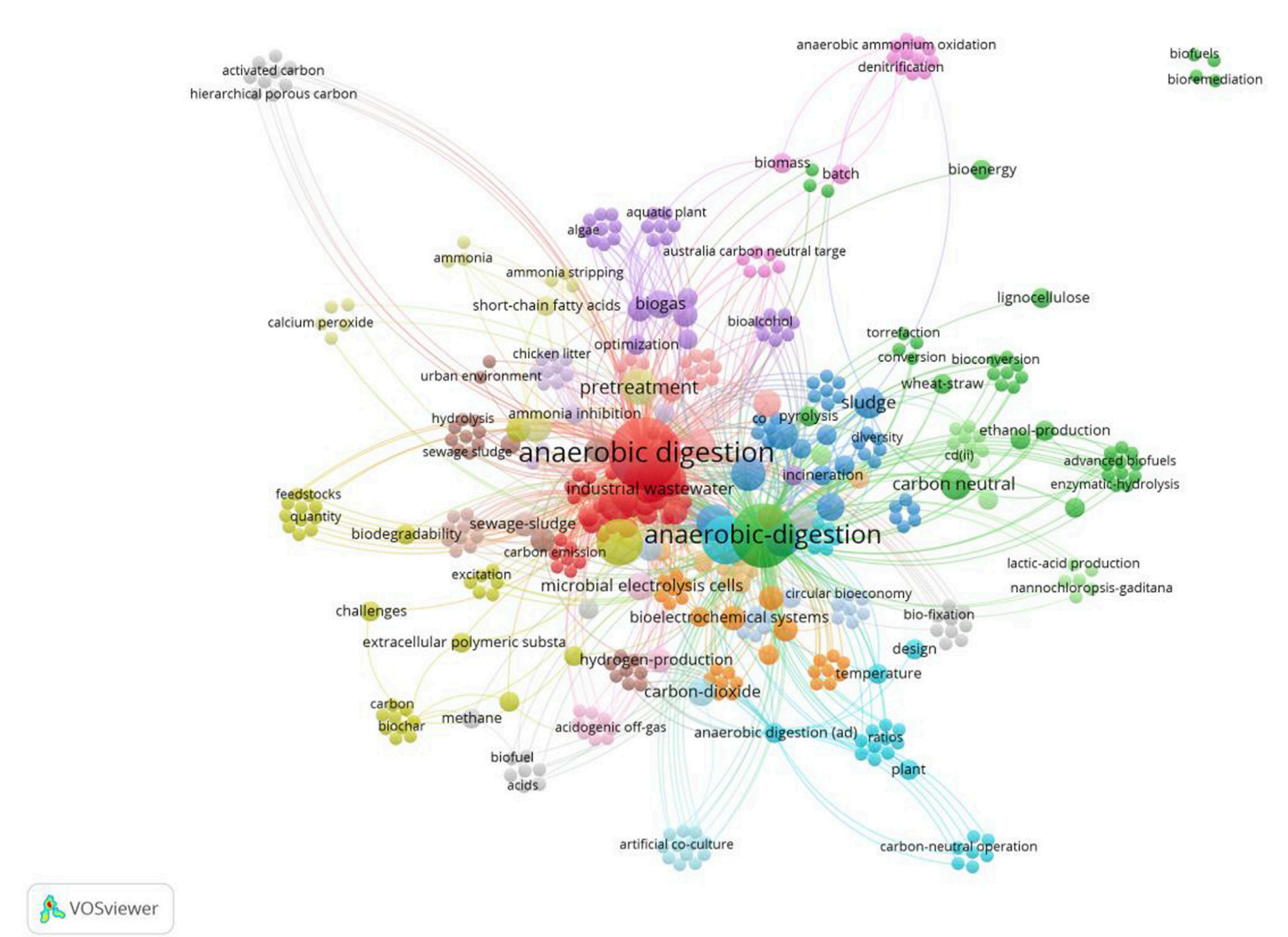

FIGURE 1
Keywords were synthesized using VOSviewer 1.6.19 software to map the carbon neutrality and anaerobic digestion results.

primarily arise from the methane (CH_4) and carbon dioxide (CO2) produced during anaerobic digestion. Methane is the second most significant greenhouse gas, with a global warming potential (GWP) value of 25, and it has a considerable impact on global climate change (Wang et al., 2025). If these gases are not effectively treated, they are released directly into the atmosphere, leading to severe environmental consequences. Methane is a potent greenhouse gas, second only to carbon dioxide, and serves as a precursor to ozone (O_3) (Mar et al., 2022). Methane has a 100-year global warming potential (GWP100) of 27.9, i.e., each kilogram of methane generates 27.9 times more radiative forcing than 1 kg of carbon dioxide over a 100-year period. Although methane itself is not classified as an air pollutant that poses direct hazards to human health, it significantly contributes to air pollution as a precursor to tropospheric ozone. Therefore, it is possible to utilize the methane produced by anaerobic digestion both as an energy source and to reduce methane emissions while reusing wastewater. Carbon dioxide, a major greenhouse gas, is associated with various environmental issues, including global warming. Carbon footprint assessment methods, such as life cycle assessment (LCA) (Müller et al., 2022), enable the quantification of carbon emissions from wastewater treatment processes and provide a scientific foundation for implementing carbon reduction strategies.

2.3 Role of anaerobic biotechnology in carbon reduction

Anaerobic biotechnology can efficiently produce methane, which can be converted into renewable energy, thereby reducing carbon emissions (Yi et al., 2024). In addition, the carbon dioxide generated during anaerobic digestion can also be utilized through carbon capture technology, further minimizing the carbon footprint of the entire treatment process. Figure 1 can indicate the distribution of literature on carbon-neutral and carbon-anaerobic processes in recent years, clearly reflecting the trends in this research area. The keywords associated with these topics are mainly focused on anaerobic digestion, wastewater treatment and carbon dioxide. The occurrence of the terms anaerobic digestion and wastewater treatment indicates that carbon neutrality is closely related to these technologies and is the key to achieving carbon neutrality. The high frequency of these keywords highlights the importance of anaerobic digestion technology and its potential application in academia. Notably, the reuse of carbon dioxide generated during anaerobic digestion is regarded as a significant contributor to achieving carbon neutrality goals. This approach not only aids in the reduction of greenhouse gas emissions but also offers new perspectives and solutions for sustainable development and further promotes the efficient recycling of resources.

TABLE 1 Key parameters and performance of anaerobic technology for wastewater treatment.

Technical name	Parameters	Raw materials	Affect	References
Expanded granular sludge bed (EGSB) bioreactor	Buffer index of 0.23 ± 0.1, pH 7.22 ± 0.4, temperature 26.6°C ± 1.4°C	Cheese whey wastewater (CWW)	The biochemical methane potential (BMP) was 92% and COD removal efficiency was 90%	Cruz-Salomón et al. (2020)
Sulfur-based autotrophic denitrification (SAD)	Different C/N	Activated sludge	showed more robustness in terms of nitrogen removal at low C/N influent	Wang et al. (2022)
Continuous flow process: anaerobic ammonia oxidation (PN/A) reactor (IBBR)	343 days of operating conditions	Garbage leachate	Partial nitrification, denitrification and anaerobic ammonia oxidation were developed in an aerated biofilter (BAF), and denitrification was carried out in an internal recirculation (IC) system, with TN removals ranging from 92.9% to 93.4%	Wu et al. (2024)
Cyclic Operation Anaerobic Membrane Bioreactor (AnMBR)	Operation at 35°C ± 1°C for 200 days	Municipal wastewater	Frequent cycling and regular permeate backflushing maintain stable membrane operation, generating energy in the form of biogas	Uman et al. (2021)
Sulfur-based autotrophic denitrification (SAD): sulfur-based fibre-carrier fixed-bed reactor (SFFR)	20°C–30°C,PH7-8	Sludge	Increased electron utilization from 75.76% to 91.8% compared to conventional SAD process. Has lower elemental sulfur consumption, lower acid production and less sludge generation	Chang et al. (2023)
Sulfur-based autotrophic disproportionation (SADP) bioreactor	Backwash the effluent at 25°C ± 1°C at a rising rate of 30 m/h		Effective integration of SADP and SADN processes	Sun et al. (2023)
Modified nitrification-anaerobic ammonia oxidation (PN/A) process	Low C/N ratio of 2.7	domestic sewage	Introduction of endogenous metabolism to construct an improved PN/A system	Dan et al. (2024)
Internal Circulation (IC) Reactor	Different organic loading rates (OLR)	Molasses wastewater	A continuous hydrogen and methane production system in a two-stage process was studied to improve energy recovery	Li and Li (2019)
Up-flow anaerobic sludge bed (UASB) process	165°C, 30 min Thermal Hydrolysis Pretreatment	Thermal Hydrolysis Sludge Dewatering Liquid	An effective waste activated sludge stabilization technology that can be stabilized at high organic loading rates (OLR) with energy recovery capabilities	Yang et al. (2022)

Table 1 demonstrates the key parameters and performance of anaerobic technologies for wastewater treatment. Cruz-Salomón et al. (Wu et al., 2024) studied an expanded granular sludge bed (EGSB) reactor, which was operated at a buffer index of 0.23 ± 0.1, a pH of 7.22 ± 0.4, and a temperature of 26.6°C ± 1.4°C, The reactor successfully treated cheese whey wastewater, achieving a biochemical methane potential (BMP) of 92% and a chemical oxygen demand (COD) removal rate of up to 90%. This technology demonstrated significant efficiency in treating wastewater with high organic loads and contributed to enhanced methane recovery. In the field of wastewater treatment, achieving "carbon neutrality" refers to optimizing processes and resource recovery so that carbon emissions from the treatment process are equal to the amount of carbon recovered or offset, with net emissions converging to zero. Anaerobic digestion can convert organic matter into methane for energy recovery, significantly reducing direct carbon emissions. However, the actual realization of carbon neutrality still faces multiple challenges, including the efficient recovery and utilization of methane, the resourcing of sludge and residues, the control of indirect carbon emissions such as energy and pharmaceuticals, and the potential fugitive emissions of greenhouse gases. Currently, some advanced wastewater plants are close to carbon neutrality through process integration and energy efficiency improvement, but further breakthroughs in technology and management are needed for large-scale popularization. Therefore, anaerobic technology provides a powerful path to carbon neutrality in wastewater treatment, but full realization still requires system synergy and continuous innovation.

3 Overview of anaerobic technology

3.1 Basic principles and process flow

Anaerobic digestion is a process in which microorganisms break organic matter into methane and carbon dioxide under anaerobic conditions (Cruz-Salomón et al., 2020; Wang et al., 2024). Table 2 illustrates the anaerobic digestion process, which consists of four distinct steps, each carried out by different groups of microorganisms that produce various products. The first step is hydrolysis, which involves the breakdown of macromolecular organic matter into simple compounds that are more readily absorbed by anaerobic microorganisms. During acid production, the hydrolyzed compounds are further degraded into organic acids, which are subsequently converted to acetic acid, the main source of energy for anaerobic methanogenic bacteria, in the process of acetogenesis. Methanogenic bacteria produce gaseous metabolites in this step, completing the final step of methane generation. The step-by-step conversion process of anaerobic digestion of wastewater includes hydrolysis, acid production, acetic acid production and methane

TABLE 2 Anaerobic digestion process.

Anaerobic digestion process				
①Hydrolysis stage Complex solid organic matter is converted to simple soluble monomers or dimers (e.g., glucose, amino acids, and long-chain fatty acids) by the action of hydrolytic enzymes	②Acidification stage Soluble substrates (degraded by microorganisms to various organic acids, hydrogen, carbon dioxide and ammonia	③Acetylation stage The molecules are further converted to acetic acid, H2 and CO2 by acetic acid-producing bacteria	④Methylation stage Anaerobic microorganisms utilize acetic acid, H_2/CO_2 to produce methane	[Complex Solid Organics] → [Hydrolysis Enzyme Action] → [Simple Soluble Monomers or Dimers] ↓ [Microbial Degradation] → [Organic Acids, H2, CO2, ammonia] ↓ [Acetogenesis Process] → [acetic acid] ↓ [Methanogenic Bacteria Action] → [Methane]

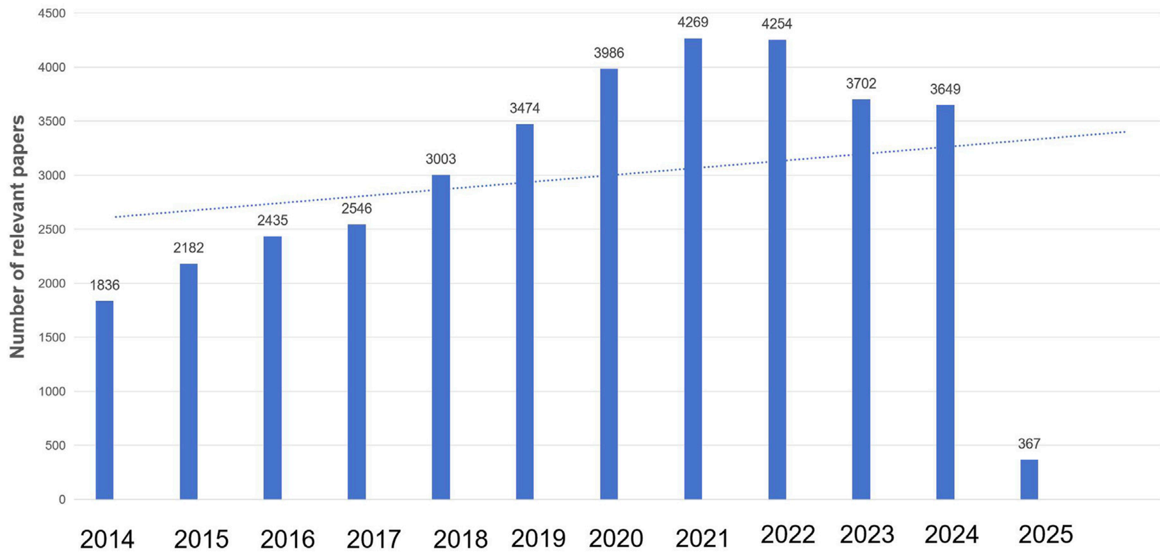

FIGURE 2
Evolution of the number of anaerobic digestion citations in literature over the last decade.

production, and each stage interacts with the other stages to jointly realize the degradation of organic matter and energy recovery.

Many countries utilize anaerobic digestion (AD) to treat wastewater and increase methane production, thereby improving economic viability (Gan et al., 2025). For example, in Malaysia, anaerobic digestion (AD) is an energy recovery method that can be used as an alternative to conventional sludge treatment technologies such as landfill and incineration. Given the large amount of food waste and sludge generated in Malaysia, anaerobic digestion not only significantly improves the efficiency of wastewater treatment, but also effectively addresses the growing food waste problem (Hanum et al., 2019). Brazil is a large tropical agricultural country with abundant natural resources. Researchers have studied the anaerobic digestion of cassava processing wastewater in Brazil to determine the optimal conditions for the production of biogas (especially carbon dioxide and methane) in order to maximize the economic benefits. Experimental results showed that a cassava wastewater to primary sludge ratio of 4:1 (i.e., 80% cassava wastewater and 20% primary sludge) resulted in the shortest fermentation time and highest methane content (Peres et al., 2019).

3.2 Technology classification

Figure 2 illustrates the growth in the number of citations for anaerobic digestion in publications over the past decade, indicating an increasing interest from the scientific community in this topic. Anaerobic biotechnology (AD) can be categorized into single-stage anaerobic digestion and multistage anaerobic digestion, depending on the process design. Single-stage anaerobic digestion refers to the scenario where all digestion reactions occur within the same reactor, while multistage anaerobic digestion involves different digestion steps carried out in multiple reactors (Van et al., 2020). Due to its operational simplicity and low cost, single-stage anaerobic digestion has been widely adopted worldwide (Jang et al., 2014). However, advancements in science and technology have led to a better understanding of the optimal growth conditions required for various digestion reactions. Although single-stage anaerobic digestion is effective in treating a wide range of wastewater and generating biogas, thereby reducing fossil energy consumption and carbon emissions, this technology may encounter challenges such as process instability and acidification (Shamurad et al., 2020).

TABLE 3 Comparison of single-stage anaerobic digestion and multistage anaerobic digestion.

Process classification	Technical name	Parameters	Raw materials	Advantages	Disadvantages	References
Single-stage anaerobic digestion process	Single-stage anaerobic digestion (AD) process	volume of 6 L, mesophilic condition (35°C ± 0.2°C)	Food wastewater	single-stage AD achieved both efficient organic removal and stable methane production from high-strength FWW.		Jang et al. (2014)
	Single-stage anaerobic digestion	Trace element (TE) supplements, co-digestion	Synthetic organic waste (SOW)	The entire digestion process is conducted in one reactor, recovering energy from the biogas at low cost		Jang et al. (2014)
	Single stage continuously stirred tank reactor (CSTR)	The reactor is maintained at 37°C ± 1°C and the hydraulic residence time (HRT) is fixed at 60 days	common sorghum		CSTR exhibited acid accumulation	Shamurad et al. (2020)
	Single-stage anaerobic digestion	Extrusion Pretreatment	Tapioca starch (CS)	The acclimatization period was significantly reduced from 41 to 23 days and increased CH4 production by 42%		Pasteris et al. (2022)
	Single-stage anaerobic digestion (SSAD)	25°C–40°C, total RT of 35 days, hydraulic retention time (HRT) 2–12 days	Wastewater	The high solids dissipation of wastewater in the SSAD process reduces biogas productivity compared to the TSAD process	After steady-state conditions are reached, the two-stage system shows superior performance, with the single-stage system averaging 45 percent methane, about nine percent less than the two-stage system	Pasteris et al. (2022)
	Single-stage partial nitrosation-anaerobic ammonia oxidation (SPNA) system	37°C, HRT 24 h	Sewage	Reaction in one reactor reduces installation area and investment costs		Fasheun et al. (2024)
Multi-stage anaerobic digestion process	Two-stage leaching bed reactor (LBR) system	Add 250–1500 g of ambient sorghum silage at a time	Common sorghum	The buffering capacity of the two-stage LBR system is superior to that of CSTR.		Pasteris et al. (2022)
	Two-stage anaerobic digestion	Extrusion Pretreatment	Tapioca starch (CS)	The acclimatization period was further reduced to 3 days and the overall CH4 productivity increased by 305%		Paranjpe et al. (2023)
	Two-stage anaerobic co-digestion process (TPAD)	The first reactor operated at 55°C and pH 5.5 and the second reactor operated at 35°C and pH 7.5	Sewage	Higher volatile fatty acid (VFA) removal and methane production, with most of the process taking place under thermophilic conditions, saving energy		Park et al. (2024)
	Multistage anaerobic ethane reactor (MAHR)	150°C, HRT was maintained at 12 h, and the pH of the inlet substrate was controlled at 7.5-7.8	Hydrothermal carbonization of wastewater (HTCWW)	Compared to an upflow anaerobic sludge blanket reactor (UASB), the MAHR process has better operational performance in handling high organic loading rates and low hydraulic retention times		Yang et al. (2023)

Anaerobic digesters can be classified into dry and wet types based on total solids (TS) content (Van et al., 2020). Dry digesters are appropriate for feedstocks with TS ≥20% and are further categorized into horizontal plug-flow, vertical plug-flow, and no-flow (batch) types. In contrast, wet digesters are appropriate for feedstocks with TS ≤15% and are commonly used in wastewater treatment. Table 3 shows a comparison between single-stage anaerobic digestion and multistage anaerobic digestion. However, acidification during single-stage digestion poses challenges that may impact its operational efficiency and stability. Multistage anaerobic digestion technology enhances solid removal and methane production during wastewater treatment by physically separating the digestion steps to optimize the reaction conditions at each stage. Multistage digestion systems typically include two- or three-stages. Two-stage systems carry out hydrolysis and methanogenesis in two separate reactors, whereas three-stage systems perform hydrolysis, acid/acetone production and methanogenesis in distinct reactors (Van et al., 2020). A two-stage system optimizes hydrolysis and acid production separately from methanogenesis, speeding up the overall digestion rate and offering numerous advantages. In a two-stage anaerobic digestion system, methanogenic bacteria thrive in an optimal environment, inhibiting the growth of other microorganisms and making the system more stable and adaptable to changes in wastewater composition. Additionally, the gas generated during hydrolysis/acidification can be directly removed from the gas collection system without further treatment, significantly reducing methane enrichment costs. Most studies indicate that two-stage systems provide superior treatment compared to single-stage systems. However, when the feedstock solids content is low (TS <3%), a two-stage system is not significantly more efficient than a single-stage system. Therefore, single-stage anaerobic digestion is more suitable for simple wastewater treatment scenarios, while multistage anaerobic digestion is ideal for treating complex wastewaters and is more effective in resource recovery. These technologies have been widely implemented in wastewater treatment plants globally, demonstrating positive environmental and economic benefits.

3.3 Technical advantages and limitations

Nevertheless, anaerobic digestion (AD) technology encounters several challenges in practical applications. First, the start-up process is lengthy due to the slow growth rate of anaerobic microorganisms; the acceleration of the start-up speed is contingent upon the sludge inoculum in the system reaching a specific concentration. Second, the operation and management of the AD system are more complex, and maintaining the microbial balance of the system is challenging because of the varying characteristics and physiological traits of the different bacteria present in the reaction system. An excessive organic matter loading rate can inhibit the activity of methanogenic bacteria and disrupt the microbial equilibrium, potentially leading to system failure. In addition, sludge AD technology faces other issues, such as intricate processes, high equipment investment costs, and substantial operational and management requirements. Therefore, optimizing and enhancing AD technology is an urgent matter that must be addressed, and these challenges can be tackled through technological innovations and process optimization (Chen W. et al., 2023).

4 Anaerobic technology for resource utilization in wastewater treatment

Methane can be produced and utilized in a number of ways and optimized, and optimizing the design of anaerobic digestion can significantly improve methane production and purity. Meanwhile, as human activities and resource consumption increase, nutrient recycling is essential for sustainable development and environmental protection. In wastewater treatment, nitrogen and phosphorus are the main causes of eutrophication in water bodies, and anaerobic biotechnology can both reduce pollution and recycle resources.

4.1 Methane generation

Figure 3 Breakdown of conventional methane generation methods (right) and front-end novel methane generation methods (left), which provides a more intuitive view of the forward-looking nature of the industry involved. Methane generation is one of the core processes of anaerobic digestion, and by optimizing the design of this process, both the yield and purity of methane can be significantly enhanced. The collected biogas is purified and treated for both power generation and transportation fuel as an alternative to natural gas, resulting in more efficient resources utilization. It is important to note that endogenous cross-linked EPS structures inhibit hydrolysis and electron transfer during methanogenesis. Recent studies have shown that humification of EPS and protein-polyphenol interactions can greatly hinder substrate accessibility and microbial activity (Tang et al., 2020; Tang et al., 2018; Tang et al., 2023). The current focus on biomethane ignores two key constraints: 1. Low energy recovery efficiency: Typically only 10%–14% (0.2 kWh/m^3) of the influent chemical energy is converted to electricity through a cogeneration system (Zeng et al., 2022). 2. Purification challenges: Fluctuating biogas composition complicates commercial upgrading. Whereas in methane production, valorizing liquid/solid residues as sustainable fertilizers or platform bioproducts (e.g., plant growth biostimulants, aromatic amino acids) can yield higher economic and environmental returns (Tang et al., 2022a; Tang et al., 2022b). To maximize energy use and enhance methane production, anaerobic digestion can be applied to a single material (monodigestion) or a mixture of multiple materials (mixed digestion or co-digestion). Anaerobic co-digestion enhances the digestion process and energy production by increasing the nutrients available to microorganisms and increasing the organic load while reducing the effects of inhibitory chemical toxicity through co-substrate dilution. In small biogas production facilities, animal manure is usually treated by single digestion, but co-digestion is commonly used in larger facilities that treat biowaste from different sources (e.g., farm, residential, and industrial). Studies have shown that co-digestion improves the stability of digestion when different feedstocks are digested simultaneously in the same reactor. Traditionally, anaerobic digestion techniques have been applied mostly to single feed materials, but in recent years, a growing body of research has shown that the co-digestion of multiple substrates makes the anaerobic digestion process more stable. Compared with single-substrate digestion, the co-digestion of multiple substrates significantly increases the biogas production potential (Lee et al., 2020). A summary of experimental parameters and research progress on the methane production performance of anaerobic digestion of various organic wastes is presented in Table 4. On the other hand, Lu et al. (2021) conducted a 25-day experiment at a constant temperature of 35°C ± 1°C to study

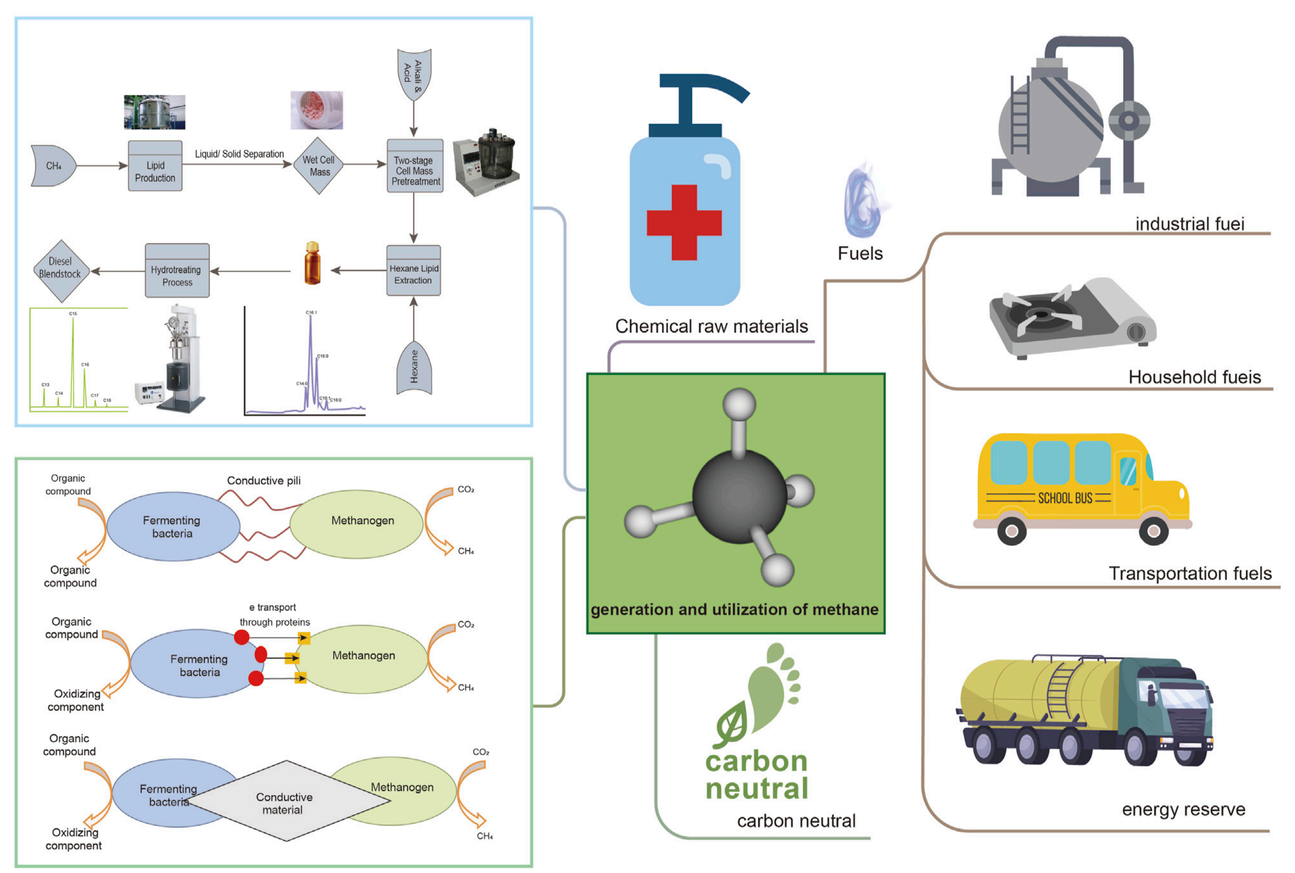

FIGURE 3
Methane generation by methanotrophic bacteria to establish the utilization of multiple carbon sources.

the enhancement of biomethane production from waste activated sludge (WAS) in anaerobic digestion. They reported that the biochemical methane potential increased by 28.1% with the addition of 0.3 g/L choline. This finding suggests that the use of choline can significantly increase methane production and provides a new pathway to optimize the energy-based treatment of waste. Darja and Goršek (2020) studied the anaerobic fermentation of mango grass and chicken manure mixtures (CMSs) under different temperature and mass ratio conditions. Their results revealed that the methane production of CMS was closely related to the fermentation temperature and mass ratio of the mixture, suggesting that the optimal design of the temperature and mass ratio in anaerobic fermentation has a significant effect on enhancing methane production. These studies provide different paths and ideas to further enhance the production efficiency of renewable energy.

4.2 Recovery and removal of nutrients from wastewater

Nutrients such as nitrogen and phosphorus contribute to eutrophication issues in aquatic ecosystems (Xie et al., 2024; Zhang et al., 2020). Anaerobic biotechnology not only addresses the issue of nitrogen and phosphorus pollution in wastewater but also recycles these nutrients through specialized techniques (Xie et al., 2025; He et al., 2017; Zhao et al., 2023). These recovered nutrients can be utilized in agricultural production as fertilizers or transformed into high-value products through additional processing, thereby maximizing the resource potential of Fang et al. (2016), Li JY. et al. (2024). As human activities and resource consumption continue to rise, nutrient recycling has become increasingly vital.

Table 5 summarizes the advancements in anaerobic biotechnology for nutrient recovery from wastewater using various raw materials. Xu et al. (2021) investigated anaerobic treatment with activated sludge, which lasted for 430 days at 31°C. This process achieved a phosphorus removal rate of 73.1% ± 6.6% of influent water and an impressive nitrogen removal efficiency of 87.8% ± 1.7%, highlighting the advantages of anaerobic processes in nutrient removal. Li JY. et al. (2024) investigated the treatment of anaerobic ammonia oxidation sludge using synthetic digestate wastewater, with the pH adjusted to 7.9 ± 0.2, and successfully achieved simultaneous nitrogen removal and phosphorus recovery, with 88.5% nitrogen removal and 83.8% phosphorus removal after 216 days of experimentation, thus demonstrating the benefits of combining anaerobic ammonia oxidation with magnesium phosphate crystallization.

TABLE 4 Summary of experimental parameters and research progress on the performance of anaerobic digestion of various organic wastes for methane production.

Raw materials	Parameters	Duration	Research progress	Bibliography
Waste activated sludge (WAS)	35°C ± 1°C	25 days	The biochemical methane potential increased by 28.1% when 0.3 g/L choline was applied	Lu et al. (2021)
Mangroves, chicken manure (CMS)	T = (32,37,39)°C, different mass ratios (80:20, 60:40 and 50:50)	21 days	CMS:M mass ratio and fermentation temperature were correlated with methane production	Darja and Goršek (2020)
Chicken manure and corn stalks	Thermophilic (37°C) and thermophilic (55°C) conditions	40 days	The accelerating effect of high temperature on the evolution of humification HA.	Wang et al. (2020a)
corn stalks	Initial total solids of 15%, 20% and 30% at 37°C ± 1°C	28 days	Long-term AD optimizes the microbial community in leachate	Li et al. (2019)
domestic sewage	HRT of 7 h	35 days	Anaerobic co-digestion with microalgae increased methane yield by 25%	Vassalle et al. (2019)
high-solids sludge	THP Pretreatment	40 days	Thermal Hydrolysis Process (THP) increases biodegradation rates, reduces retention time and increases methane production	Balasundaram et al. (2023)
Industrial kitchen waste, slaughterhouse waste, chicken manure	Methane-producing microorganisms pH 6.5-7, optimal C:N ratio 20:30		The projected annual methane production is 1,090,800 m from 40,000 tons of waste to meet the payback period of the power plant	Chowdhury (2020)
urban sewage	14°C–26°C	90 days	Lower HRT leads to lower biogas production, with methane recovery decreasing by 13% when the HRT is reduced from 12 h to 6 h. The methane recovery rate is lower when the HRT is reduced from 12 h to 6 h	Plevri and Noutsopoulos (2021)
Pepper waste (PW), swine manure (SM)	37°C ± 1°C	98 days	Methane yield increases as the percentage of PW in the mixture increases	Riaño et al. (2021)
Bagasse (SB), fresh cow dung (FBM)	35°C ± 1°C, pH 6.9–7.2		Hemicellulose hydrolysis product (HH) can be used to balance the C/N ratio	Adarme et al. (2019)
Deer manure, mushroom residue	Zeolite addition (0%, 2%, 4%, 6.25%, 8%, 10%, 12%)		The addition of zeolite and change in magnetic field conditions increased methane production	Wang et al. (2019)

4.3 Sludge treatment and resource utilization

Global sewage sludge production is rapidly growing due to the increasing demand for wastewater treatment. Effective sludge management is therefore essential for the economic and environmental sustainability of wastewater treatment plants. Recovering nutrients from sludge has been identified as a critical step in transitioning from a linear economy to a circular economy by converting sludge into an economically sustainable source of materials (Wang et al., 2017). Typically, sludge is treated through anaerobic digestion, which facilitates energy recovery through the production of biogas (Costanzo et al., 2021). Anaerobic digestion not only effectively degrades pollutants but also stabilizes and reduces sludge volume, thereby recycling resources and energy. Studies have shown that sludge has a high organic matter content, usually ranging from 35% to 52.7%, with a C/N ratio of 11.8, indicating that organic matter mineralization begins shortly after sludge digestion, making nitrogen nutrients more readily available to crops (Boumaleka et al., 2019). For example, anaerobic digestion removed 41.38, 62.26, and 68.68% of heavy metals, nutrients, persistent organic pollutants (POPs), such as polycyclic aromatic hydrocarbons (PAHs). and antibiotics and disinfection byproducts, respectively, from sludge in a sludge treatment plant in Anhui Province, China (Guo et al., 2021). The results of these studies indicate that anaerobic digestion not only enables resource recovery but also effectively reduces the emission of hazardous substances and contributes to the environmental sustainability of the wastewater treatment process (Liu et al., 2018). Table 6 summarizes the research advances in anaerobic digestion technology for sludge treatment and resource recovery. Garlicka et al. (2020) investigated the treatment of thickened primary sludge (TPS) at 36°C under different energy density conditions and reported that the energy input significantly affects methane production during anaerobic digestion. Nites et al. (2024) investigated the addition of various alkaline materials (NaOH, $Ca(OH)_2$, etc.) to the digestion of waste activated sludge over a period of 60 days and reported that the optimization of input variables such as pH had a significant effect on enhancing methane production.

5 Utilization of renewable energy sources

5.1 Biogas to energy

Anaerobic digestion of wastewater not only produces sludge but also releases significant amounts of methane gas. Due to the gradual depletion of conventional methane-generating resources, the development of nonconventional methane gas-containing fuel resources is particularly crucial. The treated biogas can be

TABLE 5 Recovery of nutrients from wastewater via anaerobic biotechnology.

Raw materials	Parameters	Duration	Research progress	Bibliography
Synthetic wastewater	Effective Volume 3 L, 25°C	140 days	The TN removal stabilized at 82.4% for the entire operating period, which was divided into three phases	Song et al. (2023)
Activated sludge	31°C ± 1°C	430 days	Removal of 73.1% ± 6.6% of influent phosphorus and high efficiency nitrogen removal was 87.8% ± 1.7%	Xu et al. (2021)
Anaerobic ammonia oxidation sludge, synthetic digestate wastewater	pH adjusted to 7.9 ± 0.2	216 days	Anaerobic ammonia oxidation with magnesium phosphate crystallization for simultaneous nitrogen removal and phosphorus recovery resulted in 88.5% nitrogen removal and 83.8% phosphorus removal	Li et al. (2024a)
Swine manure anaerobic digestion (AD) wastewater	The optimal conditions were pH 10 and a mixing time of 2 min		Under optimal conditions, the removal of NH4-N and PO4-P was approximately 74% and 83%, respectively	Ryu et al. (2020)
Synthetic wastewater	16°C ± 0.5°C, 8 h	310 days	In the mainstream process of ultralow DO, extraction of a higher percentage of supernatants is detrimental to phosphorus removal	Yu et al. (2021)
Mature sludge, synthetic wastewater	25.0°C ± 1.0°C, 48 h	60 days	Enriched denitrifying phosphorus accumulating organisms (DPAO) contributed 84% to overall phosphorus removal	Gao et al. (2023)
Granular anaerobic ammonia oxidation sludge, synthetic wastewater	25°C ± 1°C, pH 8.0–9.0	220 days	The average TN removal efficiency was 88.2% ± 1.3% and the effect of NLR on the average TP removal efficiency was not significant	Ma et al. (2020a)
Synthetic wastewater, seed sludge	HRT 6 h, 25°C ± 1°C		The final nitrogen removal achieved was 83.0% with alternating increases in influent calcium and ammonium nitrogen	Guo and Li (2020)
Sludge, synthetic wastewater	22°C ± 1°C, HRT 24 h	80 days	The average phosphorus removal efficiency of the mainstream system remained as high as 90.7% during side stream extraction	Ma et al. (2020b)
Pig manure	pH 7.6 ± 0.23, 35°C ± 1°C		In anaerobic fermentation of swine manure, acid treatment favors P release, whereas alkaline treatment does not	Chen et al. (2023b)
Wastewater and seed sludge	HRT 10.3–13.0 h	180 days	An anaerobic-oxidative-anoxic (AOA) model for the enrichment and cultivation of denitrifying phosphorus-accumulating organisms in domestic wastewater	Li et al. (2024b)

utilized for power generation or as transportation fuel, which is environmentally friendly and can enhance its economic value by utilizing the continuously generated biowaste. Furthermore, by reducing carbon emissions, biogas utilization contributes to a cleaner environment (Estrada-Arriaga et al., 2020). This use of renewable energy not only reduces the dependence on fossil fuels but also achieves energy self-sufficiency in wastewater treatment plants.

5.2 Combination of other renewable energy sources

The synergistic application of anaerobic technology in combination with other renewable energy technologies, such as solar energy and anaerobic biotechnology, can significantly improve the efficiency of energy utilization in the wastewater treatment process and provide additional renewable energy options for wastewater treatment plants (Table 7). Solar energy can assist anaerobic digestion bacteria in achieving optimal growth temperatures, thereby promoting their reproduction and improving the efficiency of both anaerobic digestion and wastewater treatment. Furthermore, the byproducts of the anaerobic digestion process can be utilized for hydrogen production, broadening the scope of renewable energy applications. The roller pond reactor (RPR) developed by Monteiro et al. (2024) employs solar energy in combination with thermal treatment to enhance the anaerobic digestion of residual sludge for efficient methane production without chemical residues. The combined vertical flow artificial wetland and solar photofenton system investigated by Cavalheri et al. (2023) targets the removal of organic matters and nutrients from wastewater, particularly emerging pollutants. Di et al. (2019) studied an integrated system to produce electrical and thermal energy based on geothermal energy, showcasing the diverse applications of renewable energy in wastewater treatment.

5.3 Energy management and optimization

To achieve energy self-sufficiency in wastewater treatment processes, it is essential to effectively manage and optimize the energy system. By implementing energy integration and optimization strategies, energy efficiency can be maximized, and operating costs can be reduced. Table 8 summarizes research progress in optimizing wastewater treatment for efficiency and resource efficiency. Ferrentino et al. (Si et al., 2022) conducted a study on the integration of water and sludge lines in a wastewater treatment plant. This integration optimized

TABLE 6 Sludge treatment and resource utilization in anaerobic digestion technology.

Raw materials	Parameters	Duration	Research progress	Bibliography
Waste Activated Sludge (WAS)	35°C ± 1°C, hydrolysis retention time 4–8 h	46 days	Thermal alkali cotreatment greatly improved methane production performance, with NaOH addition increasing methane production by 31.2% over 70°C thermal hydrolysis	Li et al. (2024c)
Waste Activated Sludge (WAS)	Thermal pretreatment (80°C, 30 min)	30 days	All the biochar prepared improved the methane production performance, with PFF-BC performing the best with a 23.4% increase in methane production	Jin et al. (2023)
Organic sludge	Heat pump heating, sludge drying, biogas cogeneration sludge anaerobic digestion, photovoltaic power generation		Reclaimed water source heat pumps can achieve higher carbon neutrality as the wastewater treatment load increases	Zhang et al. (2022)
Excessive sludge	30°C, 50°C, Add cellulose		The addition of cellulose successfully increased the hydrolysis efficiency and VFA production in anaerobic fermentation of sludge	Li et al. (2024d)
Thickened Primary Sludge (TPS)	36°C, energy density (EL = 70, 140, 210 kJ/L)	31 days	An important parameter that determines the increase in methane production during anaerobic digestion is the value of energy input to the HC process	Garlicka et al. (2020)
Sewage sludge	6–12 h, 35°C	70 days	Hydrothermal pretreatment (HTP) increases organic matter destruction and methane production	Liu et al. (2020)
Digested sewage sludge (DSS)	Pretreatment 160°C–185°C at 5°C intervals	48 days	Eighty-four percent of the organic matter in sewage sludge is converted to biogas after pretreatment with a steam explosion process (AWOEx)	Dutta et al. (2022)
High solids content sludge	HTP160, 170°C and 180°C	265 days	HTP at 160°C for 210 min favors COD dissolution and rapid methane generation as well as energy savings	Wu et al. (2020)
Waste activated sludge (WAS)	NaOH, $Ca(OH)_2$, $Mg(OH)_2$, KOH	60 days	Optimization of alkali pretreatment using input variables (pH, Cs, sCOD, TSS) had a significant effect on CH_4 enhancement	Nites et al. (2024)
Sludge digestate	pH 7.0, 37°C		THP enhanced the solubility of the digestate, thereby increasing the methane yield of the liquid hydrolysate to 175 $mLCH_4/g$	Cai et al. (2021)
Dewatered sludge, digested sludge and rice straw	15°C,25°C,30°C and 35°C	84 days	Relatively more methane was produced in soil treated with anaerobically digested sludge enhanced by hyperthermophilic pretreatment compared to unpretreated sludge	Nakamura et al. (2019)

activated sludge recirculation, improved solids removal and biogas production, and enhanced the overall system performance by integrating multiple treatment processes. On the other hand, Sanaye et al. (2023) integrated a sewage sludge anaerobic digester with a solid oxide fuel cell, resulting in a 17.86% increase in the annual yield through electrochemical reactions while reducing energy loss by 7.75%. Cengiz et al. (2024) investigated co-digestion in an anaerobic membrane bioreactor, which achieved solid-liquid separation through a membrane module, facilitated the recovery of biomethane, and improved system stability, allowing the wastewater treatment plant to achieve energy neutrality.

6 Case study

As an efficient wastewater treatment technology, anaerobic digestion has gained widespread adoption globally in recent years. Numerous successful projects have contributed valuable experience and data to its advancement. Table 9 summarizes several typical cases showing the results of different types of anaerobic digestion technologies in wastewater treatment, offering important references and insights for researchers and engineers in related fields.

Anaerobic co-digestion of water and sewage sludge at the Płaszów-Kraków municipal wastewater treatment plant has significantly increased biogas production by approximately 20% (Górka et al., 2022). This result not only enhances energy recovery efficiency but also demonstrates the substantial potential of anaerobic digestion technology for resource recovery. Through the rationalization of different types of sludge, this project has achieved energy self-sufficiency in wastewater treatment and provides a viable implementation option for other wastewater treatment plants.

On the other hand, the Tehran Wastewater Treatment Plant (TWTP) has successfully enhanced sludge hydrolysis rate through ozonation pretreatment. This method effectively disrupts bacterial cell walls, thereby enhancing the efficiency of anaerobic digestion (Hodaei et al., 2021). As an innovative technology, ozonation pretreatment offers significant advantages in enhancing sludge digestibility, which further promotes the advancement of wastewater treatment technology. The implementation of this technology not only enhances sludge treatment but also alleviates the burden of subsequent treatment stages.

TABLE 7 Renewable energy-driven wastewater treatment and resource utilization technologies.

Technical name	Principle	Affect	Bibliography
Roller Channel Pond Reactor (RPR)	The RPR is a photobioreactor that combines solar energy and thermal treatments	Enhanced anaerobic digestion (AD) of residual sludge (WAS), utilizing solar energy for methane production without chemical residues	Monteiro et al. (2024)
Solar-powered MEC	Electroactive Microorganisms (EAM)	Bioenergy recovery from wastewater can be promoted	Wang et al. (2020b)
Combined vertical flow artificial wetland and solar photofenton system	CW For the removal of pollutants such as organic matter and nutrients through biological processes	For treatment of sewage contaminated by emerging pollutants	Cavalheri et al. (2023)
Co-Hydrothermal Carbonization Process (co-HTC)	Hydrothermal carbonization (HTC) is a hygrothermal chemical process that can occur at slightly elevated temperatures and autogenous pressures	Suitable to produce alternative solid fuels	Piboonudomkarn et al. (2023)
Solar-driven interfacial water evaporation for wastewater purification	A Novel Solar Steam Generator (SVG) Based on PIC/Powdered Coal Composites (PCC)	The rational design and utilization of SVG, combined with low-cost solar absorbers, expands the practical application of SVG in WW treatment	Zuo et al. (2024)
Supercritical Water Gasification (SCWG)	Supercritical water gasification (SCWG) utilizes the superior solvent properties of water at certain temperatures and pressures to gasify wet biomass	The effluent can be fully converted to a saleable by-product, increasing gasification efficiency and reducing system operating costs	Adar et al. (2020)
An integrated system for electrical and thermal energy production based on geothermal energy utilization	Electricity produced by the ORC system: partially used to supply wastewater treatment plants	Electricity and heat can be produced for wastewater treatment plants	Di et al. (2019)
Polymer wastewater collectors	A Polymer Wastewater Collector Based on Defective Polypyrrole Modified Activated Carbon Paper Substrate (DPAC)	Provides useful insights for efficient and energy-saving treatment of domestic and industrial wastewater	Yang et al. (2022)
Gradient titanium oxide nanowire films	Gradient Titanium Oxide (GTO) nanowire films breakdown organic matter in the presence of sunlight, separating pure water and salt	The film can treat high-salt organic wastewater in sunlight	Si et al. (2022)

The use of intermittent aeration (IA) with an oxidative settling anaerobic (OSA) process at the Corleone Wastewater Treatment Plant (CWTP) demonstrated superior performance in terms of pollutant removal and sludge yield compared to the conventional activated sludge process (Mannina et al., 2024a). Notably, this process has achieved significant results in phosphorus removal. This case highlights the importance of technological innovation in enhancing the efficiency and effectiveness of wastewater treatment and offers guidance for future process optimization.

At the Juan Diaz treatment plant, the co-digestion of secondary sludges resulted in increased organic and nutrient loading, which significantly enhanced biogas production (Moretto et al., 2020). This finding suggests that a moderate increase in organic loading contributes to the efficiency of sludge treatment and promotes energy recovery and utilization. This approach not only enhances treatment effectiveness but also offers innovative strategies for achieving sustainable development goals.

The integrated anaerobic co-digestion system implemented at the Treviso Wastewater Treatment Plant (WWTP) not only achieves efficient energy recovery but also promotes the valorization of waste without the need for significant investment (Moretto et al., 2020). The principle is that ozone, as a strong oxidizing agent, can increase the degradation rate of complex organic matter and help to produce biogas through ozone pretreatment, and the effect of ozone on biogas production and other anaerobic digestion parameters of waste activated sludge depends largely on the ozone dosage and sludge residence time. This project highlights the dual benefits of economic and environmental advantages, demonstrating the significance of integrated systems in modern wastewater treatment. By strategically allocating resources and optimizing the process, the plant succeeded in developing synergies between wastewater treatment and energy recovery.

In addition, the Foligno Municipal Wastewater Treatment Plant has significantly increased biogas production, and the amount of energy recovered through the anaerobic co-digestion process (Salehiyoun et al., 2020). This result further demonstrates the importance of anaerobic co-digestion in energy recovery. By effectively combining various processes, these projects not only enhance energy recovery efficiency but also have significant potential for reducing pollutant emissions and lowering operating costs.

Overall, these success stories demonstrate the wide range of applications and significant benefits of anaerobic digestion technology in wastewater treatment worldwide. This approach not only enhances biogas production and energy recovery efficiency but also offers limitless opportunities for promoting environmental protection and sustainable resource utilization. In the future, with ongoing advancements and innovations in this technology, anaerobic digestion is expected to play a crucial role in a wider range of fields, contributing to the achievement of green and sustainable development.

TABLE 8 Optimizing wastewater treatment: improving efficiency and resource utilization.

Optimization strategy	Methods of implementation	Intended effect	Bibliography
Integrated technology in wastewater treatment plant water lines and sludge lines	Three types of processes applied in activated sludge recirculation lines were identified: mechanical, chemical, and biological	Increased removal of total volatile solids and improved biogas production	Ferrentino et al. (2023)
Anaerobic granular sludge system driven by biogas recirculation	The biogas recycling pellet UASB system is used to treat wastewater	31%–44% increase in CH_4 productivity, shorter lag time, 37%–40% increase in sludge dewaterability after digestion	Zhao et al. (2021)
Integration of sewage sludge anaerobic digesters and solid oxide fuel cells	Electrochemical reaction processes in SOFC	17.86% increase in relative annual revenue and 7.75% reduction in total energy destruction	Sanaye et al. (2023)
Co-digestion in anaerobic membrane bioreactors	In an AnMBR, the membrane module is integrated with the anaerobic bioreactor so that the membrane provides complete solid–liquid separation	Promote biomethane recovery with high stability for energy-neutralizing WWTPs	Cengiz et al. (2024)
low-frequency mechanical vibration	Two independent Anaerobic/Oxic reactors	Increases oxygen transfer coefficient and stimulates associated biological activity, effectively accelerating pollutant removal under low DO conditions	Zou et al. (2023)
Nitrification-anaerobic ammonia oxidation integrated anaerobic membrane bioreactor	Residual ammonium nitrogen contained in the AnMBR digestate effluent is further treated in a pilot-scale primary PN/A reactor	Reduces energy consumption by 0.416 kWh/m3, reduces CO_2 emissions and saves electricity costs	Zhe et al. (2022)
Preparation of sewage sludge-derived cationic aggregates	Sewage-derived cationic aggregate (SBC-g-DMC) successfully prepared by hydrothermal carbonization process combined with graft copolymerization reaction	CO emissions can be reduced, and the enriched organic matter can also be used in anaerobic fermentation to offset energy consumption	Liang et al. (2023)
Organic-rich sewage sludge as an alternative fuel to coal	The main methods of thermal conversion of SS include pyrolysis, gasification and combustion	Reduced coal consumption, increased safety and efficiency of wastewater treatment	Ni et al. (2024)
Microalgae-based coupled cerium for wastewater treatment systems	microalgal wastewater treatment with a higher range of C/N/P ratios	Promote microalgal protein synthesis, electron transfer, light utilization and antioxidant enzyme activity, and higher light utilization efficiency	Zuo et al. (2023)

TABLE 9 Examples of global anaerobic digestion wastewater treatment projects.

Name of sewage treatment plant	Types of anaerobic digestion technology	Experience and lessons learned	References
Płaszów-Kraków municipal sewage treatment plant	Anaerobic co-digestion of wastewater	Increased production of fermentation gas (biogas). Produces approximately 20% more biogas	Górka et al. (2022)
Tehran Wastewater Treatment Plant	Ozonization Pretreatment	Helps to break down the cell walls of bacteria Increases the rate of sludge hydrolysis	Hodaei et al. (2021)
Iława sewage treatment plant	Co-digestion process	AD removal efficiency is improved. Contributes to waste management Improves the facility's energy balance, reducing operating costs and pollutant emissions	Maslon et al. (2020)
Corleone Wastewater Treatment Plant	Oxidative Sedimentation Anaerobic Process (OSA) with Intermittent Aeration (IA)	The OSA-IA configuration outperformed CAS4-P removal for COD and PO, and the OSA-IA configuration produced less sewage sludge than CAS.	Mannina et al. (2024a)
Juan Diaz Treatment Plant	Co-digestion of secondary sludge (DSS)	Increase organic matter and nutrient loading during anaerobic digestion, thereby increasing biogas production	Deago et al. (2023)
Ankara Central Sewage Treatment Plant	Ultrasonic pretreatment for enhanced anaerobic digestion	Ultrasonic treatment will increase soluble organic matter, enhance organic matter removal, and improve biogas and methane production	Çelebi et al. (2020)
Treviso Wastewater Treatment Plant	Integrated anaerobic co-digestion system	Can be used directly for more energy or material recovery. Waste valorization is achieved without costly investments	Moretto et al. (2020)
Foligno Municipal Wastewater Treatment Plant	anaerobic co-digestion	Promotes biogas production, thereby significantly increasing recoverable energy	Salehiyoun et al. (2020)
Corleone Wastewater Treatment Plant	Oxygenated Settling Anaerobic (OSA) process	OSA configuration significantly increases phosphorus removal	Mannina et al. (2024b)

7 Challenges

7.1 Technical challenges

Biogas production from sewage sludge faces many research challenges. Different types of digesters, such as solid anaerobic digesters, semicontinuous solid anaerobic digesters, sewage sludge hydrothermal treatment, thermophilic digesters, two-stage anaerobic digesters (acid digesters and methanogenic digesters), double-digesting and thermophase anaerobic digesters, and bioelectrochemical anaerobic digesters, vary in their operating parameters, sizes, and sources of sludge (e.g., sewage treatment plants) (Khawer et al., 2022). Although it is becoming increasingly difficult for conventional wastewater treatment technologies to meet current demands, anaerobic biotechnology demonstrates significant potential for wastewater treatment and resource utilization. However, process optimization and stability are still technical challenges that need to be addressed. To overcome these challenges, traditional anaerobic digestion technologies need to be improved by integrating them with emerging technologies. In addition, improving resource recovery efficiency and developing efficient recycling technologies are urgent issues that must be also addressed. Currently, there are a variety of emerging technologies that not only enhance wastewater treatment and the aquatic environment but also enable more efficient utilization of the resulting sludge. These technologies achieve high resource recovery rates and play a crucial role in advancing a circular economy. For instance, microbial fuel cells (MFCs) are recognized as one of the sustainable solutions to address the excess sludge and water-energy crisis (Nikhil et al., 2018).

7.2 Economic and policy challenges

Many wastewater treatment plants still face challenges due to the complexity and high costs associated with their processes (Zhang, 2025). Despite the significant number of wastewater treatment plants in China, substantial amounts of untreated wastewater are still being discharged into rivers, and the volume of sewage continues to rise, leading to serious environmental issues. Polluted water bodies can pose a potential threat to human health, making public health issues a concern (Sanaye et al., 2023). According to a statement by the State Council, addressing water pollution and other environmental issues has been recognized as a priority, and the government is encouraging cities to build advanced wastewater treatment facilities. In 2015, the Chinese government released a new national strategy aimed at combating water pollution (Chang et al., 2018). Future experiments and practices should adopt sustainable programs that integrate multiple aspects of technology, environmental protection, health, legal considerations, economic and social aspects. The implementation of anaerobic technologies typically requires a high initial investment, while the lack and high cost of methane-fueled power generation technologies and insufficient funding can be major barriers to project advancement (Chernicharo et al., 2015). In addition, the policy and regulatory environments of different countries and regions may also affect the promotion and application of anaerobic technology. Therefore, securing adequate economic and policy support will be the key to the future development of this technology.

7.3 Social and environmental impacts

The promotion of anaerobic wastewater technology involves not only breakthroughs at the technical level but also considerations of social acceptance and public awareness (Xue et al., 2019). Currently, many people have a limited understanding of anaerobic biotechnology and may even have misconceptions. Therefore, enhancing the public's environmental awareness and comprehension of this technology is essential for fostering social acceptance. This process can be achieved by strengthening public education and the popularization of science. For instance, the government, scientific research institutions and environmental organizations can collaborate to conduct outreach activities to make the public aware of the significant potential and positive contributions of anaerobic biotechnology in waste treatment, energy recovery. and environmental protection. Moreover, policymakers and technology advocates should ensure that a comprehensive scientific assessment of the environmental impacts of anaerobic biotechnology is carried out prior to its large-scale implementation to mitigate potential negative impacts. This approach will not only help ensure the sustainable development of technology but also enhance public trust and support. Overall, social acceptance is closely related to the successful implementation of technology; thus, increasing public awareness and scientific assessment of environmental impacts are indispensable links in the promotion of anaerobic biotechnology.

8 Conclusion

"Energy self-sufficiency" in the wastewater treatment field usually means that the wastewater treatment plant itself meets all or most of its operational energy needs through energy recovery (e.g., biogas from anaerobic digestion to generate electricity) without the need for external inputs. The key ways to achieve energy self-sufficiency include: improving organic matter removal and methane production, enhancing biogas collection and utilization efficiency, optimizing energy-intensive unit processes (e.g., aeration), adopting high-efficiency equipment and energy management strategies, and may incorporate the comprehensive use of other renewable energy sources such as solar energy and heat pumps. Some advanced sewage plants have basically realized energy self-sufficiency through biogas power generation and waste heat recovery, providing a demonstration of green and low-carbon transformation for the industry. The full realization of energy self-sufficiency requires synergistic innovation in process, equipment, management and other aspects.

In the context of "carbon neutrality", the application of anaerobic biotechnology in wastewater treatment and resource utilization demonstrates significant potential. Studies have shown that anaerobic digestion can effectively reduce carbon dioxide emissions from wastewater treatment while converting organic matter into methane, a renewable energy source. This technology not only helps reduce greenhouse gas emissions but also facilitates resource recycling, aligning with the principles of a circular economy. While traditional wastewater treatment methods involve high energy consumption and significant carbon emissions, anaerobic technology, which uses the metabolic activities of anaerobic microbial populations, not only reduces the release of carbon dioxide but also provides energy for wastewater treatment plants by generating methane. Anaerobic digestion technology is increasingly being studied, including the comparison of single-stage and multistage digestion, the optimization of different reactors, and the recovery of nutrients such as nitrogen and phosphorus. These studies highlight the ability of multistage anaerobic digestion to optimize treatment conditions at different stages, thereby improving overall efficiency. Case studies have shown that the use of anaerobic co-digestion in several wastewater treatment plants has significantly increased biogas production and improved energy recovery efficiency. Combining other renewable energy technologies, such as solar energy, with anaerobic biotechnology has also further improved energy efficiency. Overall, anaerobic biotechnology provides an important solution for achieving a low-carbon transition in wastewater treatment, with multiple benefits in terms of resource utilization, energy recovery and environmental protection.

The importance of anaerobic biotechnology in the field of wastewater treatment is becoming increasingly apparent with the advancement in technology. Due to its efficient performance in terms of carbon reduction and resource recovery, it holds considerable potential for various applications. In the future, the development of anaerobic biotechnology will focus on technological innovation and diverse implementations. Moreover, integrating anaerobic biotechnology with other technologies will also provide additional opportunities to achieve the carbon neutrality goal of wastewater treatment. Among the available high-rate anaerobic technologies, the front-end technology is mainly the membrane bioreactor. Since the performance of membranes cannot be scaled up directly from the laboratory to actual plants, further research is needed to facilitate the implementation of this technology in large-scale wastewater treatment plants.

Author contributions

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References

Abeydeera, LHUW, Mesthrige, J. W., and Samarasinghalage, T. L. (2019). Global research on carbon emissions: a scientometric review. *Sustainability* 11, 3972. doi:10.3390/su11143972

Adar, E., Ince, M., and Bilgili, M. S. (2020). Supercritical water gasification of sewage sludge by continuous flow tubular reactor: a pilot scale study. *Chem. Eng. J.* 391, 123499. doi:10.1016/j.cej.2019.123499

Adarme, O. F. H., Baêta, B. E. L., Filho, J. B. G., Gurgel, L. V. A., and Aquino, S. F. D. (2019). Use of anaerobic co-digestion as an alternative to add value to sugarcane biorefinery wastes. *Bioresour. Technol.* 287, 121443. doi:10.1016/j.biortech.2019.121443

Balasundaram, G., Gahlot, P., Tyagi, V. K., and Kazmi, A. A. (2023). Advanced steam explosion as thermal hydrolysis process for high solids anaerobic digestion and enhanced methane yield: proof of concept. *Sustain. Chem. Pharm.* 36, 101274. doi:10.1016/j.scp.2023.101274

Boumaleka, W., Kettab, A., Bensacia, N., Maria, C., Bruzzoniti, O. D. B., Mandi, L. M., et al. (2019). Specification of sewage sludge arising from a domestic wastewater treatment plant for agricultural uses. *Desalination Water Treat.* 143, 178–183. doi:10.5004/dwt.2019.23559

Cai, C., Hu, C. L., Yang, W., Hua, Y., Li, L., Yang, D. H., et al. (2021). Sustainable disposal of excess sludge: post-Thermal hydrolysis for anaerobically digested sludge. *J. Clean. Prod.* 321, 128893. doi:10.1016/j.jclepro.2021.128893

Cavalheri, P. S., Machado, B. S., da Silva, T. F., Rodrigues, JPBG, Gozzi, F., Filho, FJCM, et al. (2023). Optimization of a combined system of vertical flow constructed wetland and solar photo-Fenton for ketoprofen removal in sewage and landfill leachate. *Chem. Eng. J.* 475, 146282. doi:10.1016/j.cej.2023.146282

Çelebi, E. B., Aksoy, A., and Sanin, F. D. (2020). Effects of anaerobic digestion enhanced by ultrasound pretreatment on the fuel properties of municipal sludge. *Environ. Sci. Pollut. Res.* 27, 17350–17358. doi:10.1007/s11356-020-08230-4

Cengiz, A. I., Guven, H., Ozgun, H., and Ersahin, M. E. (2024). Enhanced energy recovery in municipal wastewater treatment plants through co-digestion by anaerobic membrane bioreactors: current status and future perspectives. *Rev. Environ. Sci. Bio/Technology* 23, 385–410. doi:10.1007/s11157-024-09691-6

Chang, M. D., Fan, F. L., Zhang, K., Wu, Z., Zhu, T., and Wang, Y. Z. (2023). Denitrification performance and mechanism of a novel sulfur-based fiber carrier fixed-bed reactor: co-Existence of sulfur-based autotrophic denitrification and endogenous denitrification. *J. Water Process Eng.* 53, 103618. doi:10.1016/j.jwpe.2023.103618

Chang, N. B., Lu, J. W., Chui, T. F. M., and Hartshorn, N. (2018). Global policy analysis of low impact development for stormwater management in urban regions. *Land Use Policy* 70, 368–383. doi:10.1016/j.landusepol.2017.11.024

Chen, T., Song, X. M., and Xing, M. (2023b). Study on anaerobic phosphorus release from pig manure and phosphorus recovery by vivianite method. *Sci. Rep.* 13, 16095. doi:10.1038/s41598-023-43216-5

Chen, W., Wang, J., and Liu, W. G. (2023a). A view of anaerobic digestion: microbiology, advantages and optimization. *Acad. J. Environ. and Earth Sci.*, 2616–5872. doi:10.25236/AJEE.2023.050101

Cheng, Y. P., Wang, L., and Zhang, X. L. (2011). Environmental impact of coal mine methane emissions and responding strategies in China. *Int. J. Greenh. Gas Control* 5, 157–166. doi:10.1016/j.ijggc.2010.07.007

Chernicharo, C. A. L., Lier, J. B. V., Noyola, A., and Bressani Ribeiro, T. (2015). Anaerobic sewage treatment: state of the art, constraints and challenges. *Rev. Environ. Sci. Biotechnol.* 14, 649–679. doi:10.1007/s11157-015-9377-3

Chowdhury, H. (2020). Technical-economical analysis of anaerobic digestion process to produce clean energy. *Energy Rep.* 7, 247–253. doi:10.1016/j.egyr.2020.12.024

Costanzo, N. D., Cesaro, A., Capua, F. D., and Esposito, G. (2021). Exploiting the nutrient potential of anaerobically digested sewage sludge: a review. *Energies* 14, 8149. doi:10.3390/en14238149

Cruz-Salomón, A., Ríos-Valdovinos, E., Pola-Albores, F., Lagunas-Rivera, S., Cruz-Rodríguez, R. I., Cruz-Salomón, K. C., et al. (2020). Treatment of cheese whey wastewater using an expanded granular sludge bed (EGSB) bioreactor with biomethane production. *Processes* 8, 931. doi:10.3390/pr8080931

Dan, Q. P., Wang, T., Li, J. W., Zhang, Q., and Peng, Y. Z. (2024). Enhanced anammox performance under lower nitrite accumulation in modified partial nitritation-anammox (PN/A) process. *Bioresour. Technol.* 406, 131018. doi:10.1016/j.biortech.2024.131018

Darja, P., and Goršek, A. (2020). Kinetics of methane production during anaerobic digestion of chicken manure with sawdust and miscanthus. *Biomass Bioenergy* 143, 105820. doi:10.1016/j.biombioe.2020.105820

Deago, E., Ramírez, M., Espino, K., Nieto, D., Barragán, M., García, M., et al. (2023). Optimizing anaerobic digestion at ambient temperatures: energy efficiency and cost reduction potential in Panama. *Water* 15, 2653. doi:10.3390/w15142653

Di, F. S., Macaluso, A., Massarotti, N., and Vanoli, L. (2019). Energy, exergy and economic analysis of a novel geothermal energy system for wastewater and sludge treatment. *Energy Convers. Manag.* 195, 533–547. doi:10.1016/j.enconman.2019.05.035

Dutta, N., Giduthuri, A. T., Khan, M. U., Garrison, R., and Ahring, B. K. (2022). Improved valorization of sewage sludge in the circular economy by anaerobic digestion: impact of an innovative pretreatment technology. *Waste Manag.* 154, 105112. doi:10.1016/j.wasman.2022.09.035

Estrada-Arriaga, E. B., Reynoso-Deloya, M. G., Guillén-Garcés, R. A., Falcón-Rojas, A., and García-Sánchez, L. (2020). Enhanced methane production and organic matter removal from tequila vinasses by anaerobic digestion assisted *via* bioelectrochemical power-to-gas. *Bioresour. Technol.* 320, 124344. doi:10.1016/j.biortech.2020.124344

Fang, C., Zhang, T., Jiang, R. F., and Ohtake, H. (2016). Phosphate enhance recovery from wastewater by mechanism analysis and optimization of struvite settleability in fluidized bed reactor. *Sci. Rep.* 6, 32215. doi:10.1038/srep32215

Fasheun, D. O., Silva, ASAD, Teixeira, R. S. S., and Ferreira-Leitão, V. S. (2024). Enhancing methane production from cassava starch: the potential of extrusion pretreatment in single-stage and two-stage anaerobic digestion. *Fuel* 366, 131406. doi:10.1016/j.fuel.2024.131406

Ferrentino, R., Langone, M., Fiori, L., and Andreottola, G. (2023). Full-scale, sewage sludge reduction technologies: a review with a focus on energy consumption. *Water* 15, 615. doi:10.3390/w15040615

Gan, B., Li, Z., Huo, W., Zhang, Y., Li, Z., Fan, R., et al. (2025). Phase transitions of CH4 hydrates in mud-bearing sediments with Oceanic laminar distribution: mechanical response and stabilization-type evolution. *Fuel* 380, 133185. doi:10.1016/j.fuel.2024.133185

Gao, M. C., Sun, S. F., Qiu, Q., Zhou, W. W., and Qiu, L. P. (2023). Enrichment denitrifying phosphorus-accumulating organisms in alternating anoxic-anaerobic/aerobic biofilter for advanced nitrogen and phosphorus removal from municipal wastewater. *J. Water Process Eng.* 55, 104089. doi:10.1016/j.jwpe.2023.104089

Garlicka, A., Zubrowska-Sudol, M., Umiejewska, K., Roubinek, O., Palige, J., and Chmielewski, A. (2020). Effects of thickened excess sludge pre-treatment using hydrodynamic cavitation for anaerobic digestion. *Energies* 13, 2483. doi:10.3390/en13102483

Górka, J., Cimochowicz-Rybicka, M., and Poproch, D. (2022). Sludge management at the kraków-płaszów WWTP—Case study. *Sustainability* 14, 7982. doi:10.3390/su14137982

Guo, Y., and Li, Y. Y. (2020). Hydroxyapatite crystallization-based phosphorus recovery coupling with the nitrogen removal through partial nitritation/anammox in a single reactor. *Water Res.* 187, 116444. doi:10.1016/j.watres.2020.116444

Guo, Y. Q., Guo, Y. L., Gong, H., Fang, N., Tan, Y. Q., Zhou, W. Q., et al. (2021). Variations of heavy metals, nutrients, POPs and particle size distribution during "Sludge anaerobic digestion-solar drying-land utilization process": case study in China. *Sci. Total Environ.* 801, 149609. doi:10.1016/j.scitotenv.2021.149609

Hanum, F., Lee, C. Y., Kamahara, H., Aziz, H. A., Atsuta, Y., Yamada, T., et al. (2019). Treatment of sewage sludge using anaerobic digestion in Malaysia: current state and challenges. *Front. Energy Res.* 7, 00019. doi:10.3389/fenrg.2019.00019

He, X. M., Zhang, T., Ren, H. Q., Li, G. X., Ding, L. L., and Pawlowski, L. (2017). Phosphorus recovery from biogas slurry by ultrasound/H2O2 digestion coupled with HFO/Biochar adsorption process. *Waste Manag.* 60, 219–229. doi:10.1016/j.wasman.2016.08.032

Hodaei, M., Ghasemi, S., Khosravi, A., and Vossoughi, M. (2021). Effect of the ozonation pretreatment on biogas production from waste activated sludge of Tehran wastewater treatment plant. *Biomass and Bioenergy* 152, 106198. doi:10.1016/j.biombioe.2021.106198

Jang, H. M., Kim, J. H., Ha, J. H., and Park, J. M. (2014). Bacterial and methanogenic archaeal communities during the single-stage anaerobic digestion of high-strength food wastewater. *Bioresour. Technol.* 165, 174–182. doi:10.1016/j.biortech.2014.02.028

Jin, H. Y., He, Z. W., Ren, Y. X., Zou, Z. S., Tang, C. C., Zhou, A. J., et al. (2023). Revealing the roles of biochar derived from iron-rich fermented sludge residue in anaerobic digestion. *Chem. Eng. J.* 481, 148376. doi:10.1016/j.cej.2023.148376

Jin, S. Q., Zhang, B., Wu, B., Han, D. M., Hu, Y., Ren, C. C., et al. (2021). Decoupling livestock and crop production at the household level in China. *Nat. Sustain.* 4, 48–55. doi:10.1038/s41893-020-00596-0

Khawer, M. U. B., Naqvi, S. R., Ali, L., Arshad, M., Anjum, M. W., and Naqvi, M. (2022). Anaerobic digestion of sewage sludge for biogas and biohydrogen production: state-Of-The-Art trends and prospects. *Fuel* 329, 125416. doi:10.1016/j.fuel.2022.125416

Lee, J. K., Hong, J. S., Jeong, S., Chandran, K., and Park, K. Y. (2020). Interactions between substrate characteristics and microbial communities on biogas production yield and rate. *Bioresour. Technol.* 303, 122934. doi:10.1016/j.biortech.2020.122934

Li, B. Q., Tang, Y., Xiao, X. N., Tang, X., Luo, D., Liu, Y. X., et al. (2024c). Enhanced anaerobic digestion of waste-activated sludge by thermal–alkali pretreatment: a pilot-scale study. *Water Sci. Technol.* 90, 303–313. doi:10.2166/wst.2024.210

Li, J. Y., Chen, Z. G., Zhang, Y. Z., Zhang, Y., Yang, J. F., Li, B. Q., et al. (2024a). Simultaneous nitrogen removal and phosphorus recovery by anammox-induced magnesium phosphate mineralization: interaction mechanism between microorganisms and mineral formation. *ACS Sustain. Chem. and Eng.* 12, 7392–7401. doi:10.1021/acssuschemeng.4c00473

Li, Q. Y., and Li, Y. F. (2019). Coproduction of hydrogen and methane in a CSTR-IC two-stage anaerobic digestion system from molasses wastewater. *Water Sci. Technol.* 79 (042), 270–277. doi:10.2166/wst.2019.042

Li, S., Yin, Y., and Zhang, R. (2024d). The impacts of cellulose on volatile fatty acid production and the microbial community in anaerobic fermentation of sludge at high and medium temperatures. *Appl. Biochem. Biotechnol.* 9, 05052. doi:10.1007/s12010-024-05052-9

Li, Y. Q., Wang, Z. X., Li, T., Jiang, S. H., Sun, Z. Y., Jiang, H., et al. (2019). Changes in microbial community and methanogenesis during high-solid anaerobic digestion of ensiled corn stover. *J. Clean. Prod.* 242, 118479. doi:10.1016/j.jclepro.2019.118479

Li, Z. X., Li, X. Y., Wang, H. B., and Peng, Y. Z. (2024b). Achieving synchronous and highly efficient removal of nitrogen and phosphorus by rapid enrichment and cultivation denitrifying phosphorus accumulating organisms in anaerobic-oxic-anoxic operation mode. *Bioresour. Technol.* 396, 130426. doi:10.1016/j.biortech.2024.130426

Liang, H., Shan, S. J., Li, X. Y., Li, D. P., and Huang, Y. (2023). Preparation of cationic aggregates derived from sewage sludge for efficient capture of organic matter. *Chemosphere* 333, 138909. doi:10.1016/j.chemosphere.2023.138909

Liu, G., Xu, Q., Abou-Elwafa, S. F., Ali Alshehri, M., and Zhang, T. (2024). Hydrothermal carbonization technology for wastewater treatment under the "Dual Carbon" goals: current status, trends, and challenges. *Water* 16, 1749. doi:10.3390/w16121749

Liu, W., Zheng, J., Liu, X., Song, Y., Tian, C., Rong, W., et al. (2018). Effective extraction of Cr(VI) from hazardous gypsum sludge *via* controlling the phase transformation and chromium species. *Environ. Sci. Technol.* 52, 13336–13342. doi:10.1021/acs.est.8b02213

Liu, X. G., Wang, Q., Tang, Y. Z., and Pavlostathis, S. G. (2020). Hydrothermal pretreatment of sewage sludge for enhanced anaerobic digestion: resource transformation and energy balance. *Chem. Eng. J.* 410, 127430. doi:10.1016/j.cej.2020.127430

Lu, Y., Yuan, H. P., Zhu, N. W., and Shen, Y. W. (2021). How does choline change methanogenesis pathway in anaerobic digestion of waste activated sludge. *Energy* 224, 120171. doi:10.1016/j.energy.2021.120171

Ma, H. Y., Xue, Y., Zhang, Y. F., Kobayashi, T., Kubota, K., and Li, Y. Y. (2020a). Simultaneous nitrogen removal and phosphorus recovery using an anammox expanded reactor operated at 25 °C. *Water Res.* 172, 115510. doi:10.1016/j.watres.2020.115510

Ma, J., Yang, R. C., Yu, X. J., Zhao, Y. T., Sang, Q. Q., Wang, F. J., et al. (2020b). Investigation of anaerobic side-stream phosphorus recovery and its effect on the performance of mainstream EBPR subjected to low-consumption. *Water Sci. Technol.* 80, 1944–1955. doi:10.2166/wst.2020.014

Ma, X. J., Wang, C. X., Dong, B. Y., Gu, G. C., Chen, R. M., Li, Y. F., et al. (2019). Carbon emissions from energy consumption in China: its measurement and driving factors. *Sci. Total Environ.* 648, 1411–1420. doi:10.1016/j.scitotenv.2018.08.183

Mannina, G., Cosenza, A., Di, T. D., Gulhan, H., Mineo, A., and Mofatto, P. M. B. (2024b). Reduction of sewage sludge and N2O emissions by an oxic settling anaerobic (OSA) process: the case study of corleone (italy) wastewater treatment plant. *Sci. Total Environ.* 906, 167793. doi:10.1016/j.scitotenv.2023.167793

Mannina, G., Mofatto, P. M. B., Cosenza, A., Di Trapani, D., Gulhan, H., Mineo, A., et al. (2024a). The effect of aeration mode (intermittent vs. continuous) on nutrient removal and greenhouse gas emissions in the wastewater treatment plant of corleone (italy). *Sci. Total Environ.* 924, 171420. doi:10.1016/j.scitotenv.2024.171420

Mar, K. A., Unger, C., Walderdorff, L., and Butler, T. (2022). Beyond CO2 equivalence: the impacts of methane on climate, ecosystems, and health. *Environ. Sci. Policy* 134, 127–136. doi:10.1016/j.envsci.2022.03.027

Maslon, A., Czarnota, J., Szaja, A., Szulzyk-Cieplak, J., and Lagód, G. (2020). The enhancement of energy efficiency in a wastewater treatment plant through sustainable biogas use: case study from Poland. *Energies* 13, 6056. doi:10.3390/en13226056

Monteiro, J. P., Cruzeiro, C., Salomé, D. M., Alcina, P. M., and Vilar, V. P. (2024). Innovative waste activated sludge pre-treatment using a raceway pond. *Chem. Eng. J.* 498, 155324. doi:10.1016/j.cej.2024.155324

Moretto, G., Ardolin, P. A., Girotto, L., and Cecchi, F. (2020). Integrated anaerobic co digestion system for the organic fraction of municipal solid waste and sewage sludge treatment: an Italian case study. *J. Chem. Technol. Biotechnol.* 95, 418–426.

Müller, L. J., Kätelhön, A., Bringezu, S., Sean, M. C., Suh, S., Edwards, R. S. V., et al. (2022). The carbon footprint of the carbon feedstock CO2. *Energy Environ. Sci.* 13, 2979–2992. doi:10.1039/D0EE01530J

Nakamura, M., Hidaka, T., Yamaoka, M., and Oritate, F. (2019). Methane production and nitrogen mineralization in paddy soil treated with sludge from anaerobic digestion enhanced by hyperthermophilic pretreatment. *Paddy Water Environ.* 17, 447–454. doi:10.1007/s10333-019-00740-3

Negri, C., Ricci, M., Zilio, M., D'Imporzano, G., Wei, Q., Dong, R., et al. (2020). Anaerobic digestion of food waste for bio-energy production in China and southeast Asia: a review. *Renew. Sustain. Energy Rev.* 133, 110138. doi:10.1016/j.rser.2020.110138

Ni, Z. S., Zhang, Y. K., Liu, X., Shi, H., Yao, Y. R., Tian, J. J., et al. (2024). Effect of furnace temperature and oxygen concentration on combustion and CO/NO emission characteristics of sewage sludge. *Renew. Energy* 234, 121225. doi:10.1016/j.renene.2024.121225

Nikhil, G. N., Krishna, C. D. N. S., Srikanth, S., Swamy, Y. V., and Venkata, M. S. (2018). Applied resistance for power generation and energy distribution in microbial fuel cells with rationale for maximum power point. *Chem. Eng. J.* 335, 267–274. doi:10.1016/j.cej.2017.10.139

Nites, M., Singh, D., Yadav, B. R., Tembhare, M., and Kumar, S. (2024). Optimizing alkali-pretreatment dosage for waste-activated sludge disintegration and enhanced biogas production yield. *Environ. Res.* 252, 118876. doi:10.1016/j.envres.2024.118876

Paranjpe, A., Saxena, S., and Jain, P. (2023). Biogas yield using single and two stage anaerobic digestion: an experimental approach. *Energy Sustain. Dev.* 74, 6–19. doi:10.1016/j.esd.2023.03.005

Park, J., Song, M. S., Hwang, K., and Bae, H. (2024). Start-up strategy of single-stage partial nitrification-anammox process for anaerobic digestion effluent. *Bioresour. Technol.* 408, 131213. doi:10.1016/j.biortech.2024.131213

Pasteris, A. M., Heiermann, M., Theuerl, S., Plogsties, V., Jost, C., Prochnow, A., et al. (2022). Multi-advantageous sorghum as feedstock for biogas production: a comparison between single-stage and two-stage anaerobic digestion systems. *J. Clean. Prod.* 358, 131985. doi:10.1016/j.jclepro.2022.131985

Peres, S., Monteiro, M. R., Ferreira, M. L., Junior, AFDN, and Mdlapf, P. (2019). Anaerobic digestion process for the production of biogas from cassava and sewage treatment plant sludge in Brazil. *Bioenerg. Res.* 12, 150–157. doi:10.1007/s12155-018-9942-z

Piboonudomkarn, S., Khemthong, P., Youngjan, S., Wantala, K., Tanboonchuy, V., Lubphoo, Y., et al. (2023). Co-hydrothermally carbonized sewage sludge and lignocellulosic biomass: an efficiently renewable solid fuel. *Arabian J. Chem.* 16, 105315. doi:10.1016/j.arabjc.2023.105315

Plevri, D. M., and Noutsopoulos, C. (2021). Anaerobic MBR technology for treating municipal wastewater at ambient temperatures. *Chemosphere* 275, 129961. doi:10.1016/j.chemosphere.2021.129961

Riaño, M.-S., Molinuevo-Salces, B., Parralejo, A., Royano, L., González-Cortés, J., and García-González, M. C. (2021). Techno-economic evaluation of anaerobic co-digestion of pepper waste and swine manure. *Biomass Conv.* 13, 7763–7774. doi:10.1007/s13399-021-01831-0

Ryu, H.-D., Lim, D. Y., Kim, S.-J., Baek, U.-I., Chung, E. G., Kim, K., et al. (2020). Struvite precipitation for sustainable recovery of nitrogen and phosphorus from anaerobic digestion effluents of swine manure. *Sustainability* 12, 8574. doi:10.3390/su12208574

Salehiyoun, A. R., Di, M. F., Sharifi, M., Norouzi, O., Zilouei, H., and Aghbashlo, M. (2020). Anaerobic co-digestion of sewage sludge and slaughterhouse waste in existing wastewater digesters. *Renew. Energy* 145, 2503–2509. doi:10.1016/j.renene.2019.08.001

Sanaye, S., Imeni, M., and Yazdani, M. (2023). Clean production of power and heat for wastewater treatment plant by integrating sewage sludge anaerobic digester and solid oxide fuel cell. *Energy Convers. Manag.* 288, 117136. doi:10.1016/j.enconman.2023.117136

Shamurad, B., Sallis, P., Petropoulos, E., Tabraiz, S., Ospina, C., Leary, P., et al. (2020). Stable biogas production from single-stage anaerobic digestion of food waste. *Appl. Energy* 263, 114609. doi:10.1016/j.apenergy.2020.114609

Si, P. C., Wang, Q. H., Kong, H. R., Li, Y. T., and Wang, Y. (2022). Gradient titanium oxide nanowire film: a multifunctional solar energy utilization platform for high-salinity organic sewage treatment. *Acs Appl. Mater. and Interfaces* 14, 19652–19658. doi:10.1021/acsami.2c00793

Song, Y., Ni, J. L., Guo, Y., Kubota, K., Qi, W. K., and Li, Y. Y. (2023). Anammox upflow hybrid reactor: nitrogen removal performance and potential for phosphorus recovery. *Chemosphere* 313, 137580. doi:10.1016/j.chemosphere.2022.137580

Springmann, M., Clark, M., Croz, D. M. D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., et al. (2018). Options for keeping the food system within environmental limits. *Nature* 562, 519–525. doi:10.1038/s41586-018-0594-0

Sun, Y. L., Zheng, K., Zhai, S. Y., Cheng, H. Y., Qian, Z., Wang, H. C., et al. (2023). A novel pattern of coupling sulfur-based autotrophic disproportionation and denitrification processes for achieving high-rate and precisely adjustable nitrogen removal. *Chem. Eng. J.* 476, 146772. doi:10.1016/j.cej.2023.146772

Tang, Y. F., Dai, X. H., Dong, B., Guo, Y. Q., and Dai, L. L. (2020). Humification in extracellular polymeric substances (EPS) dominates methane release and EPS reconstruction during the sludge stabilization of high-solid anaerobic digestion. *Water Res.* 175, 115686. doi:10.1016/j.watres.2020.115686

Tang, Y. F., Li, X. W., Dong, B., Huang, J. J., Wei, Y. H., Dai, X. H., et al. (2018). Effect of aromatic repolymerization of humic acid-like fraction on digestate phytotoxicity reduction during high-solid anaerobic digestion for stabilization treatment of sewage sludge. *Water Res.* 143, 436–444. doi:10.1016/j.watres.2018.07.003

Tang, Y. F., Sun, J., Dong, B., and Dai, X. H. (2022a). Thermal hydrolysis pretreatment-anaerobic digestion promotes plant-growth biostimulants production from sewage sludge by upregulating aromatic amino acids transformation and quinones supply. *Environ. Sci. and Technol.* 56, 1938–1950. doi:10.1021/acs.est.1c06506

Tang, Y. F., Sun, J., Dong, B., and Dai, X. H. (2023). Citric acid treatment directly on anaerobic digestor sludge alleviates the inhibitory effect of *in-situ* generated humic acids by their deconstruction and redistribution. *Water Res.* 233, 119680. doi:10.1016/j.watres.2023.119680

Tang, Y. F., Xie, H., Sun, J., Li, X. O., Zhang, Y., and Dai, X. H. (2022b). Alkaline thermal hydrolysis of sewage sludge to produce high-quality liquid fertilizer rich in nitrogen-containing plant-growth-promoting nutrients and biostimulants. *Water Res.* 211, 118036. doi:10.1016/j.watres.2021.118036

Uman, A. E., Bair, R. A., and Yeh, D. H. (2021). Assessment of an anaerobic membrane bioreactor (AnMBR) treating medium-strength synthetic wastewater under cyclical membrane operation. *Membranes* 11, 415. doi:10.3390/membranes11060415

Van, D. P., Fujiwara, T., Tho, B. L., Toan, P. P. S., and Minh, G. H. (2020). A review of anaerobic digestion systems for biodegradable waste: configurations, operating parameters, and current trends. *Environ. Eng. Res.* 25, 1–17. doi:10.4491/eer.2018.334

Vassalle, L., Díez-Montero, R., Machado, A. T. R., Moreira, C., Ferrer, I., Mota, C. R., et al. (2019). Upflow anaerobic sludge blanket in microalgae-based sewage treatment: co-Digestion for improving biogas production. *Bioresour. Technol.* 300, 122677. doi:10.1016/j.biortech.2019.122677

Wang, B., Liu, W. Z., Zhang, Y. F., and Wang, A. J. (2020b). Bioenergy recovery from wastewater accelerated by solar power: intermittent electro-driving regulation and capacitive storage in biomass. *Water Res.* 1175, 115696. doi:10.1016/j.watres.2020.115696

Wang, H., Xu, J., Sheng, L., Liu, X., Zong, M., and Yao, D. (2019). Anaerobic digestion technology for methane production using deer manure under different experimental conditions. *Energies* 12, 1819. doi:10.3390/en12091819

Wang, H. C., Liu, Y., Yang, Y. M., Fang, Y. K., Luo, S., Cheng, H., et al. (2022). Element sulfur-based autotrophic denitrification constructed wetland as an efficient approach for nitrogen removal from low C/N wastewater. *Water Res.* 226, 119258. doi:10.1016/j.watres.2022.119258

Wang, H. T., Yang, Y., Keller, A. A., Li, X., Feng, S. J., Dong, Y. N., et al. (2016). Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa. *Energy* 184, 873–881. doi:10.1016/j.apenergy.2016.07.061

Wang, J., Liu, S. T., Feng, K., Lou, Y., Ma, J., and Defeng, X. D. F. (2025). Anaerobic digestion of lignocellulosic biomass: process intensification and artificial intelligence. *Renew. Sustain. Energy Rev.* 210, 115264. doi:10.1016/j.rser.2024.115264

Wang, R., Wang, Z., Yuan, H., Li, C., and Zhu, N. (2024). Mechanistic exploration of COVID-19 antiviral drug ritonavir on anaerobic digestion through experimental validation coupled with metagenomics analysis. *J. Hazard. Mater.* 479, 135603. doi:10.1016/j.jhazmat.2024.135603

Wang, X. Q., Muhmood, A., Lyu, T., Dong, R. J., Liu, H. T., and Wu, S. B. (2020a). Mechanisms of genuine humic acid evolution and its dynamic interaction with methane production in anaerobic digestion processes. *Chem. Eng. J.* 408, 127322. doi:10.1016/j.cej.2020.127322

Wang, Y. C., Zhang, T., Westerhoff, P., Jiang, R. F., Ren, H. Q., Yang, Y., et al. (2017). Microwave-assisted digestion and NaOH treatment of waste-activated sludge to recover phosphorus by crystallizing struvite. *Environ. Technol.* 38, 1211–1222. doi:10.1080/09593330.2016.1220630

Wu, L. J., Li, X. X., Liu, Y. X., Yang, F., Zhou, Q., Ren, R. P., et al. (2020). Optimization of hydrothermal pretreatment conditions for mesophilic and thermophilic anaerobic digestion of high-solid sludge. *Bioresour. Technol.* 321, 124454. doi:10.1016/j.biortech.2020.124454

Wu, L. N., Zhang, Y. L., Yin, J., Luo, A. T., Tian, Y. H., Liu, Y. F., et al. (2024). Achieving advanced nitrogen removal from mature landfill leachate in continuous flow system involving partial nitrification-anammox and denitrification. *Bioresour. Technol.* 399, 130553. doi:10.1016/j.biortech.2024.130553

Xie, S. Y., He, X. Y., Ali, A. M., Abou-Elwafa, S. F., and Zhang, T. (2024). Elevated effect of hydrothermal treatment on phosphorus transition between solid-liquid phase in swine manure. *Results Eng.* 24, 102887. doi:10.1016/j.rineng.2024.102887

Xie, S. Y., Zhang, T., You, S. M., Mukherjee, S., Pu, M. J., Chen, Q., et al. (2025). Applied machine learning for predicting the properties and carbon and phosphorus fate of pristine and engineered hydrochar. *Biochar* 7, 19. doi:10.1007/s42773-024-00404-4

Xu, Q., Zhang, T., Niu, Y. Q., Mukherjee, S., Abou-Elwafa, S. F., Nguyen, N. S. H., et al. (2024). A comprehensive review on agricultural waste utilization through sustainable conversion techniques, with a focus on the additives effect on the fate of phosphorus and toxic elements during composting process. *Sci. Total Environ.* 942, 173567. doi:10.1016/j.scitotenv.2024.173567

Xu, W. J., Zhang, T. Y., Wan, J. F., Li, H. S., Chen, Y., and Wang, Y. (2021). Phosphorus recovery *via* the formation of hydroxyapatite crystals at various nitrogen loading rate in an anammox-based UAFB. *Bioresour. Technol.* 326, 124628. doi:10.1016/j.biortech.2020.124628

Xue, Q., He, X. Y., Sachs, S. D., Becker, G. C., Zhang, T., and Kruse, A. (2019). The current phosphate recycling situation in China and Germany: a comparative review. *Front. Agric. Sci. Eng.* 6, 403–418. doi:10.15302/j-fase-2019287

Yang, H., Si, B. C., Huang, S. J., Wu, H. K., and Liu, Z. D. (2023). Efficient anaerobic digestion of hydrothermal carbonization wastewater *via* an innovative multistage anaerobic hythane reactor (MAHR): organic conversion and microbial evolution. *J. Environ. Chem. Eng.* 11, 110179. doi:10.1016/j.jece.2023.110179

Yang, T. Z., Wang, S., Benetti, D., Wang, K. H., Sun, Y. W., Ji, H. Q., et al. (2022). Efficient solar domestic and industrial sewage purification *via* polymer wastewater collector. *Chem. Eng. J.* 428, 131199. doi:10.1016/j.cej.2021.131199

Yi, X., Wang, Z., Zhao, P., Song, W., and Wang, X. (2024). New insights on destruction mechanisms of waste activated sludge during simultaneous thickening and digestion process *via* forward osmosis membrane. *Water Res.* 254, 121378. doi:10.1016/j.watres.2024.121378

Yu, X. J., Tian, W. Q., Deng, Y., Cai, Y. Q., Wang, Y. E., Wang, Z. L., et al. (2021). Nutrient removal and phosphorus recovery performance of an anaerobic side-stream extraction based enhanced biological phosphorus removal subjected to low dissolved oxygen. *J. Water Process Eng.* 42, 101861. doi:10.1016/j.jwpe.2020.101861

Zeng, Q., Zan, F. X., Hao, T. W., Khanal, S. K., and Chen, G. H. (2022). Sewage sludge digestion beyond biogas: electrochemical pretreatment for biochemicals. *Water Res.* 208, 117839. doi:10.1016/j.watres.2021.117839

Zhang, Q. L., Yang, Y. X., Zhang, X. C., Liu, F., and Wang, G. (2022). Carbon neutral and techno-economic analysis for sewage treatment plants. *Environmental Technology and Innovation.* 26, 102302. doi:10.1016/j.eti.2022.102302

Zhang, T. (2025). Sustainable wastewater treatment and the circular economy. *Water* 17 (3), 335. doi:10.3390/w17030335

Zhang, T., Li, Q. C., Ding, L. L., Ren, H. Q., Xu, K., Wu, Y. G., et al. (2011). Modeling assessment for ammonium nitrogen recovery from wastewater by chemical precipitation. *J. Environ. Sci.* 23, 881–890. doi:10.1016/s1001-0742(10)60485-8

Zhang, T., Wu, X. S., Shaheen, S. M., Zhao, Q., Liu, X. J., Rinklebe, J., et al. (2020). Ammonium nitrogen recovery from digestate by hydrothermal pretreatment followed by activated hydrochar sorption. *Chem. Eng. J.* 379, 122254. doi:10.1016/j.cej.2019.122254

Zhao, J. M., Hou, T. T., Wang, Q., Zhang, Z. Y., Lei, Z. F., Shimizu, K., et al. (2021). Application of biogas recirculation in anaerobic granular sludge system for multifunctional sewage sludge management with high efficacy energy recovery. *Appl. Energy* 298, 117212. doi:10.1016/j.apenergy.2021.117212

Zhao, Z. P., Wang, B., Feng, Q. W., Chen, M., Zhang, Y., and Zhao, R. H. (2023). Recovery of nitrogen and phosphorus in wastewater by red mud-modified biochar and its potential application. *Sci. Total Environ.* 860, 160289. doi:10.1016/j.scitotenv.2022.160289

Zhe, K., Yi, X., Yanlong, Z., Tianwei, H., Hong, C., Sun, J. L., et al. (2022). Insights into the carbon neutrality for the treatment process engineering of municipal wastewater by anaerobic membrane bioreactor integrated with partial nitritation-anammox: CO2 reduction and energy recovery. *J. Water Process Eng.* 49, 102996. doi:10.1016/j.jwpe.2022.102996

Zou, L. Z., Zhang, H. L., Liu, D. Y., Jiang, W. J., Xu, W. M., Cheng, H., et al. (2023). A novel insight into energy conservation and efficiency enhancement in wastewater treatment process: low-Frequency mechanical vibration induced. *J. Water Process Eng.* 52, 103492. doi:10.1016/j.jwpe.2023.103492

Zuo, W., Chen, Z. W., Zhang, J., Zhan, W., Yang, H. L., Li, L. P., et al. (2023). The microalgae-based wastewater treatment system coupled with cerium: a potential way for energy saving and microalgae boost. *Environ. Sci. Pollut. Res.* 30, 60920–60931. doi:10.1007/s11356-023-26639-5

Zuo, Z. C., Zhu, F. B., Wang, L., Wang, Z. Q., Zhao, J. H., Ji, Z. T., et al. (2024). Trapping waste metal ions in a hydrogel/coal powder composite for boosting sewage purification *via* solar-driven interfacial water evaporation with long-term durability. *Chem. Eng. J.* 481, 148524. doi:10.1016/j.cej.2024.148524