water

MDPI

Review

The Promotion of Anaerobic Digestion Technology Upgrades in Waste Stream Treatment Plants for Circular Economy in the Context of "Dual Carbon": Global Status, Development Trend, and Future Challenges

Xinjia Huang

Bartlett School of Sustainable Construction, University College London, London WC1E 6BT, UK; ucbvxh2@ucl.ac.uk

Abstract: This review provides a comprehensive overview of the advancements and challenges of anaerobic digestion technology in waste stream treatment plants under the framework of the circular economy, emphasizing its role in achieving "dual carbon" goals. As climate change intensifies, with waste stream treatment contributing significantly to global emissions, there is a pressing need to optimize energy efficiency and reduce carbon outputs in this sector. Anaerobic digestion is highlighted as a solution for converting organic waste into renewable biogas and digestate, enabling energy self-sufficiency and reducing greenhouse gasses. The study highlights that anaerobic digestion enables the conversion of organic waste into renewable biogas and nutrient-rich digestate, facilitating energy self-sufficiency and significant reductions in GHG emissions. Successful implementations, such as in Weifang, China, demonstrate the feasibility of upgrading biogas into biomethane for local energy use. Advanced technologies like bioelectrochemical methanation and membrane bioreactors enhance biogas production efficiency, while co-digestion proves effective even in challenging conditions. Despite these advancements, the review identifies critical challenges, including high investment costs, technical inefficiencies, and regulatory barriers, particularly in developing countries. This study provides insights into integrating anaerobic digestion with circular economy principles and offers a foundation for future policies and research aimed at achieving carbon neutrality and sustainable waste management.

Keywords: bioenergy recovery; sustainable waste management; carbon neutrality; energy efficiency; green technologies

check for updates

Citation: Huang, X. The Promotion of Anaerobic Digestion Technology Upgrades in Waste Stream Treatment Plants for Circular Economy in the Context of "Dual Carbon": Global Status, Development Trend, and Future Challenges. *Water* **2024**, *16*, 3718. https://doi.org/10.3390/w16243718

Academic Editor: Fanying Kong

Received: 16 November 2024
Revised: 7 December 2024
Accepted: 10 December 2024
Published: 23 December 2024

Copyright: © 2024 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In recent years, the increase in greenhouse gas (GHG) emissions has exacerbated global climate change, leading to widespread adverse effects worldwide. The frequent occurrence of extreme weather events, such as hurricanes, floods, and droughts, poses significant threats to human life and economic development, while rising sea levels force mass migrations from coastal areas and further contribute to international instability [1]. In response to these challenges, the United Nations adopted 17 Sustainable Development Goals in 2015, urging countries to take immediate action to combat climate change. Later that year, the Paris Agreement was established during the Paris Climate Conference, requiring nations to reduce GHG emissions and limit global temperature rise to well below 2 °C, with efforts to cap the increase at 1.5 °C [2]. As one of the largest global emitters of carbon dioxide, China has also accelerated its transition towards a green economy. In 2020, the country announced its commitment to peaking carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060 [3]. Subsequently, the 2021 Action Plan for Peaking CO_2 Emissions by 2030 emphasized industrial restructuring, improving energy efficiency, and promoting green technologies [4].

Despite significant progress across several sectors, waste stream treatment has often been overlooked due to its perception as a low-carbon industry. However, wastewater treatment involved in the waste stream treatment is an energy-intensive process, contributing nearly 5% of global non-carbon dioxide emissions, which is projected to rise to 22% by 2030 [5]. Additionally, electricity consumption in the sewage sector is expected to increase by 80% over the next 25 years [6]. Therefore, advancing technological solutions to achieve energy self-sufficiency and reducing carbon emissions in this sector has become a critical priority.

Anaerobic digestion technology is a well-established and widely applied method in sewage treatment, capable of breaking down organic wet waste and sewage sludge under anaerobic conditions. Through microbial activity, these materials are converted into biogas and digestate, producing both renewable energy and recyclable fertilizers [7–9]. This process not only reduces reliance on fossil fuels but also significantly curtails GHG emissions. Despite these benefits, the current global economy remains heavily dependent on a linear economic model, which is based on extracting raw materials from nature, converting them into products, and ultimately disposing of them as waste [10]. Over the past decades, this linear approach has led to severe pollution and resource depletion, exacerbating both the climate and environmental crises. In contrast, circular economic strategies—focused on the efficient use of industrial materials and the recycling of resources to generate renewable energy—offer a sustainable alternative. These strategies can significantly reduce global greenhouse gas emissions while enhancing resilience to extreme weather and natural disasters [11–13].

However, it is important to note that while recent advancements in digitization and intelligent applications have enhanced the ability of anaerobic digestion systems to convert organic waste into biogas, several technical and economic bottlenecks still hinder their large-scale deployment. These challenges include efficiency limitations that are highly sensitive to external factors, technological gaps related to scalability, as well as high initial investment costs and extended payback periods.

This review aims to examine how anaerobic digestion technology can facilitate the transition of waste stream treatment towards a circular economy. By analyzing the current global development of anaerobic digestion technology in waste stream treatment, the study will explore the key drivers and challenges, including technological advancements, policy frameworks, and market demand, while anticipating future trends. Finally, the review will synthesize existing research and practices, highlighting the essential role of anaerobic digestion technology in advancing circular economic principles. This will provide a scientific foundation and valuable insights to guide future research and policymaking.

2. Overview of Anaerobic Digestion Techniques

2.1. Basic Principles and Techniques of Anaerobic Digestion

Anaerobic digestion is a biological process in which microorganisms break down organic matter in an oxygen-free environment. Common organic feedstocks include animal manure, food waste, agricultural residues, and wastewater solids [8,9,14]. Through this process, organic matter is converted into methane and carbon dioxide, primarily to produce biogas. The material remaining after digestion, known as digestate, is nutrient-rich and can be separated into solid and liquid fractions, both of which are commonly used as fertilizers for crops. In wastewater treatment, the by-products of digestion are often referred to as biosolids [15].

Notably, while digestate is a nutrient-rich by-product of anaerobic digestion, containing high levels of nitrogen, phosphorus, and potassium that are valuable for improving soil fertility and promoting sustainable agricultural practices, it may not always be suitable for direct agricultural use. Factors such as high salinity, heavy metal contamination, and the presence of pathogens or organic pollutants can negatively impact crop health and soil ecosystems [16]. Furthermore, logistical challenges, including high transportation costs and regulatory restrictions, may further constrain its agricultural application [17]. In some instances, alternative uses, such as bioplastic production, conversion into biochar, or energy recovery through incineration, may present more viable and efficient options [18].

As shown in Figure 1, the anaerobic digestion process for converting organic waste into biogas involves four main stages: hydrolysis, acidification, acetogenesis, and methanogenesis [19]. In the hydrolysis stage, hydrolytic bacteria decompose complex organic compounds into simpler molecules, breaking down carbohydrates, proteins, and fats into amino acids, sugars, and long-chain fatty acids. In the subsequent acidogenesis phase, fermenting bacteria converts these monomers into volatile fatty acids, organic acids, and alcohols, with the potential release of ammonia and hydrogen sulfide. During acetogenesis, acetic acid-forming bacteria convert the volatile fatty acids into acetic acid, carbon dioxide, and hydrogen. Finally, in the methanogenesis stage, methanogens convert acetic acid and hydrogen into a mixture of methane and carbon dioxide.

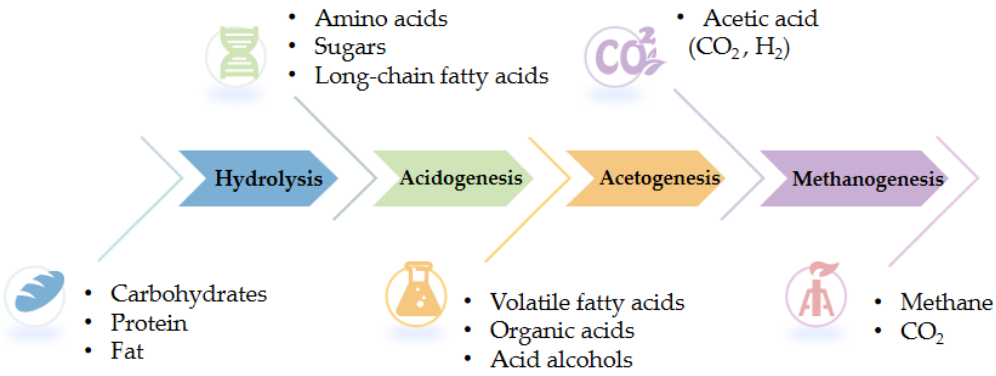


Figure 1. The four main stages of anaerobic digestion of organic waste.

As shown in Figure 2, anaerobic digestion technology can be categorized based on factors such as moisture content of the raw material, feed frequency, and mixing method. First, digesters are classified as either wet or dry systems. Wet digesters are suitable for substrates like sewage sludge and animal manure with a moisture content above 85%, while dry digesters are ideal for biosolid waste and food waste with a solids content exceeding 15% [20]. Second, based on feed frequency, digesters are categorized into batch and continuous systems; batch digesters produce biogas periodically, whereas continuous digesters generate biogas at a relatively stable rate [21]. In practice, many digesters operate in a semi-batch or semi-continuous mode, balancing biogas production continuity with routine maintenance needs. Finally, mixing methods for digesters vary between non-fixing and fully fixing systems. Fully fixing digesters, utilizing mechanical agitation and biogas recirculation, provide a uniform digestion environment and prevent temperature gradients or "dead zones" [22]. Although fully mixed digesters incur higher operating costs, these are partially offset by enhanced biogas yields.

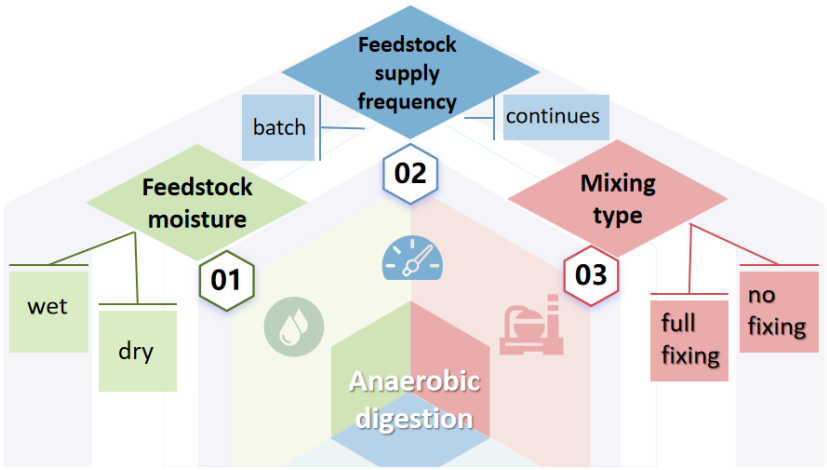


Figure 2. The main design parameters of anaerobic digestion technology.

2.2. Application Status of Anaerobic Digestion Technology in Wastewater Treatment

Anaerobic digestion technology has garnered significant attention due to its broad applications in climate and environmental protection, as well as its potential economic benefits. As an efficient waste management strategy, anaerobic digestion is widely applied in sewage sludge treatment, effectively reducing treatment costs and energy consumption. It also produces high-calorific biogas, which can be used for power generation, enabling plants to achieve energy self-sufficiency [23]. Additionally, the integration of cogeneration technology allows facilities not only to fulfill their own heating needs but also to supply thermal energy to surrounding areas, further enhancing economic benefits [20].

The application of anaerobic digestion technology varies significantly across regions. In Europe, stringent environmental regulations and renewable energy policies have driven the widespread adoption of this technology, particularly in Germany and the Nordic countries, where a mature industrial chain has formed. In Germany, the Renewable Energy Act (EEG) of 2000 spurred the development of biogas power, leading to the establishment of over 1000 biogas plants within 14 years [24]. Today, Germany is one of the world's largest biogas producers, and wastewater treatment plants often co-digest food and agricultural waste with sludge, enhancing anaerobic digestion efficiency [25]. In contrast, the development of anaerobic digestion technology in the United States has been propelled by technological innovations and advancements in pretreatment methods, which have significantly improved sludge decomposition rates and biogas production [26].

Compared to developed countries in Europe and the United States, developing nations face technical, economic, and policy-related challenges in adopting anaerobic digestion technology. In Malaysia, for instance, wastewater treatment largely relies on traditional methods despite technical potential due to resource limitations. Although European co-digestion methods have been applied to improve efficiency, results have been limited by inadequate technical support [27]. Similarly, African countries face barriers such as insufficient funding, technology, and policy frameworks, further complicated by inadequate infrastructure. In countries like Kenya and Uganda, the government has initiated biogas programs, but a lack of systematic support has hindered project sustainability [28]. To overcome these challenges, targeted strategies are needed in these regions, including enhanced technical training, increased public awareness, improved policy support, and strengthened international collaboration and financial assistance.

2.3. Economic and Environmental Benefits of Anaerobic Digestion Technology

The primary advantages of anaerobic digestion technology in the sewage treatment industry are twofold: economic benefits and environmental gains. First, as shown in Table 1, anaerobic digestion offers significant economic benefits by reducing fossil fuel costs associated with sludge incineration in wastewater treatment plants through biogas production and utilization. Additional revenue is generated through cogeneration and by-product sales, such as biogas electricity and reduced fertilizer input costs [29]. While large systems entail substantial capital investment, proper management and government incentives can enhance their economic feasibility.

From an environmental perspective, anaerobic digestion minimizes the combustion and emissions of organic waste, effectively reducing greenhouse gas emissions and supporting sustainable development [30]. In Japan, the anaerobic digestion project in Minamisanriku Town reduces waste disposal costs and increases local revenue by lowering incineration and landfill requirements. This project annually produces 2150 tons of liquid fertilizer and 255 tons of high-value rice, resulting in a 216.5% increase in net income when operational efficiency reaches 100%. Concurrently, greenhouse gas emissions are reduced to 126 kg CO_2-eq per ton of waste, marking an approximate 23% decrease [31]. In Russia's Sverdlovsk region, a sewage treatment plant generates approximately 9.9 million cubic meters of biogas annually, which is converted into 20.8 million kWh of electricity and 24.78 million kWh of heat, addressing regional energy demands. This €65.18 million investment promotes green infrastructure and reduces annual CO_2 emissions by 119,649 tonnes,

accounting for 0.45% of the region's total wastewater treatment emissions [32]. Anaerobic digestion technology not only transforms sludge into biofertilizers and energy, aligning with circular economy principles, but also mitigates the risks associated with sludge treatment and alleviates environmental burdens.

Based on the analysis of various countries presented in Table 1, the application of anaerobic digestion technology generally yields substantial economic returns, primarily reflected in cost savings, increased net income, and enhanced energy efficiency, particularly in energy production and technological advancements. In terms of environmental benefits, most countries report significant reductions in greenhouse gas emissions, highlighting notable progress in sustainable development. Furthermore, energy efficiency and infrastructure investment are closely interconnected, with many countries benefiting from increased energy capacity and efficiency, especially those facing high energy demand. Factors influencing these outcomes include the economic context, environmental policies, energy demand, and technological innovation. For instance, wealthier countries and those with established energy industries are more likely to invest heavily in anaerobic digestion technologies, while environmental policies and technological innovations contribute to more substantial environmental benefits.

Table 1. Economic and environmental benefits of anaerobic digestion technology by region.

Region	Economic Benefit	Environmental Benefit	Energy Benefit	Infrastructure Investment	Reference
Japan	Net income increase by 216.5%	GHG reduction by approx. 23%	Production of 2150 tons of liquid fertilizer	Annual investment required: 5375 GBP	[31]
Russia	Green investment return of USD 651.8 million	Annual emission reduction of 11,964 tons, 0.45% to total emissions	Production of 2080 MWh of electricity and 2478 MWh of heat	Nationwide facility investment required: USD 651.8 million	[32]
Iran	Net income increases by 45.2%	Reduction in global warming potential by 79.16–92.65%	Total cumulative generation over 20 years: 4571.7 GWh	Average LCOE: USD 0.0335–0.0426 per kWh	[33]
China	Annual net profit: USD 7.85–11.67 million	Annual emission reduction of 785.4–3301.6 Mt CO_2-eq	Annual gas production: 17,090 m^3	Construction cost: USD 30–75 million	[20]
Germany	65% return on recycling and high technology reuse	20,000 tons GHG reduction	Annual production capacity: 980 million m^3	Upgrade investment required: USD 65 million	[34]
UK	Annual sales revenue: GBP 38.73 million	3–10% annual emission reduction	Annual production of approx. 1200 MWh of electricity	Construction cost: USD 10 million	[35]
Argentina	Energy cost savings of 35%	Better Acidification potential emission reduction effect	Methane purity after concentration: 65%	Average facility cost: USD 2 million	[36]
Spain	Income of EUR 973.59 million	79–80% reduction in GHG emissions	Annual capacity of 666.88 MWh of energy	Payback period: 3–5 years	[37]
USA	10-year lifecycle cost savings of USD 20.5 million	79.16–92.65% reduction in GHG emissions	CHP systems raise efficiency up to 80%	Capital investment: USD 12.3–16.4 million	[38]
Turkey	Savings of USD 1.3 billion in fossil fuel imports	12.2 Mt CO_2-eq reduction in emissions	Annual capacity of approx. 95 MWe of electricity	Initial investment: USD 21.71 million; payback period: 5–8 years	[39]

3. Status of Anaerobic Digestion Technology Upgrade in Global Wastewater Treatment Plants

3.1. Upgrade and Progress of Anaerobic Digestion Technology

As shown in Table 2, wastewater treatment plants worldwide are increasingly recognizing the potential of anaerobic digestion technology and actively pursuing technological upgrades. In terms of capacity enhancement, efficiency has been notably improved by optimizing operational conditions and implementing two-stage or multi-stage anaerobic digestion systems. These advanced configurations enhance the production of high value-added products, such as volatile fatty acids (VFAs) and hydrogen, by carefully adjusting

pH, temperature, and the residence time of organic waste [40]. Integrating continuous stirred-tank reactors (CSTR) with upflow anaerobic sludge blanket (UASB) reactors has further boosted biogas yields, while two-stage anaerobic digestion has achieved 10% to 30% increases in methane production [41]. However, large-scale applications are constrained by high capital investment and operational complexity. Future developments should focus on large-scale testing, optimizing solid–liquid separation, and improving energy efficiency.

Second, smaller wastewater treatment plants with limited infrastructure have enhanced the production efficiency of methane and biofertilizers by employing photosynthetic biogas upgrading and bioelectrochemical methanation technologies. Photosynthetic biogas upgrading utilizes microalgae photosynthesis to fix CO_2 in the biogas, thus purifying it [42], while bioelectrochemical methanation applies voltage to facilitate CO_2 reduction and methane production [43]. However, due to the operational instability of these technologies, their scalabilities face significant challenges and the application remains limited to laboratory and small-scale settings, with industrial implementation requiring further research. Limitations include low current densities during large-scale applications, high capital and operational costs due to complex electrode and reactor designs, and sensitivity to operational parameters like pH and temperature. Additionally, issues such as biofouling, reduced efficiency in real wastewater environments, and difficulty maintaining electroactive microbial communities further constrain their industrial feasibility [44].

In wastewater treatment, anaerobic membrane bioreactors (AnMBRs), which integrate anaerobic digestion with membrane separation technology, overcome the limitations of traditional anaerobic reactors. This approach enables efficient treatment of urban sewage under low-temperature and low-organic-load conditions, achieving methane recovery rates as high as 99.5% [42]. Despite advances that have reduced the cost of membrane separation, the relatively low economic value of methane has driven wastewater treatment plants to explore its potential for producing high-value volatile fatty acids (VFAs). Current advancements in nanofiltration (NF), reverse osmosis (RO), and pervaporation (PV) membrane technologies have improved both the transmission rate and selectivity of VFAs [45]. Although AnMBRs can yield high-quality effluent by controlling hydraulic power and solid retention time [46], challenges remain, including membrane fouling, temperature fluctuations, and sulfate-induced corrosion, all of which require further resolution.

During anaerobic digestion, improper substrate composition, loading rates, or process parameters can lead to reaction interruptions, reduced biogas yields, or even complete process failure, resulting in economic losses for wastewater treatment plants. Studies indicate that adding substances such as ash, biochar, or zero-valent iron can help stabilize pH, create microbial habitats, and remove contaminants, thus optimizing reaction conditions and enhancing methane production [20]. Among these, biochar not only adsorbs inhibitory compounds like NH_3 and H_2S but also serves as a hydrogen transfer medium, promoting syntrophic metabolism and improving anaerobic digestion performance [47]. Biochar shows promising potential for application in small to medium-sized wastewater treatment plants, though its effectiveness on a larger scale requires further validation.

Hydrogen addition technology also holds promising applications. By adding H_2, hydrogenotrophic methanogens can convert H_2 and CO_2 into methane, thereby increasing the methane content in biogas [48]. Researchers at Aarhus University in Denmark developed a GasMix injection system to introduce H_2 into a full-scale thermophilic anaerobic reactor, achieving approximately a 45% increase in hydrogen conversion [49]. Although hydrogen conversion remains constrained by gas–liquid mass transfer, the successful operation of the GasMix system offers an effective solution for efficient and cost-effective hydrogen mass transfer in large-scale anaerobic digestion. Future studies can further optimize injector design and operational parameters to enhance performance.

Additionally, anaerobic digestion of single substrates tends to perform poorly in cold regions. To address this, wastewater treatment plants employ co-digestion technology, which improves the carbon-to-nitrogen ratio by mixing high-carbon substrates, such as crop residues, with high-nitrogen substrates in organic wastewater. This approach enhances the

system's buffering capacity and helps prevent pH fluctuations. For example, in Tibet, China, studies have demonstrated that co-digesting wheat straw with wastewater sludge at a 9:1 ratio significantly increases biogas production at a low temperature of 15 °C, compared to the digestion of a single substrate [50]. Pretreatment techniques also play a crucial role in low-temperature anaerobic digestion. Methods such as using ultrasonic waves to break down organic particles or adjusting pH and moisture levels can improve substrate-microorganism contact, enhancing the digestion rate and methane yield [51]. In cold regions like Canada, the northern United States, and Northern Europe, various pretreatment technologies and reactor designs have been developed to sustain microbial activity under low temperatures, mitigating the adverse effects of cold on anaerobic digestion.

Table 2. The upgrading and progress of various anaerobic digestion technologies.

Upgrade Technology	Features	Advantages	Limitations	Application Prospects	Reference
Capacity Improvement	Optimization of pH, temperature, and retention time	Increased biogas yield, VFAs, and ammonia production	High capital investment; complex operation	Medium to small scale; experimental facilities	[40]
Reactor Combination	CSTR combined with UASB	10–30% increase in methane yield	Complex operation; higher costs	Small to medium scale; wastewater treatment plants	[41]
Phototrophic Bioreactor Upgrade	Microalgae-assisted purification	Increased methane purity	Difficult to scale up; high land area requirement	Small scale, decentralized; wastewater treatment	[42]
Bioelectrochemical Methanation	Generation of external voltage	Suitable for small-scale devices; current in experimental phase	System instability under high current densities	Laboratories and small scale applications	[43]
Membrane Bioreactor	Coupled membrane separation technology	Methane purity rate up to 99.5%	Membrane contamination; Temperature fluctuation effect	Medium to large scale; wastewater treatment	[42]
Membrane Application	Nanofiltration, reverse osmosis, and pervaporation	Increased VFAs production; mitigates membrane fouling issues	High maintenance costs	Small to medium scale wastewater treatment	[45,46]
Additives Technology	Addition of ash, biochar, etc.	pH regulation; inhibition of by-products; enhanced digestibility	Unproven on a large scale	Medium to small scale; experimental facilities	[20,47]
Ammonia Stripping	Injection of air and gas recirculation	Increased ammonia removal efficiency; improved mass transfer	Gas–liquid limitations; sensitive to operating conditions	Medium to large scale	[49]
Co-Substrate Technology	High-protein biomass co-digestion with organic substrates	Improved system stability and methane yield	Limited substrates in cold climates	Cold-climate regions; wastewater treatment plants	[50,52]

3.2. Case Studies of the Current Situation in Various Regions of the World

In Europe, stringent environmental regulations and supportive policies have driven the widespread adoption and advancement of anaerobic digestion technology, particularly in the treatment of sewage sludge and agricultural waste. As shown in Table 3, integrated anaerobic digestion and composting (IADC) is commonly used for organic waste treatment, with a focus on optimizing biogas productivity [53]. The EU's circular economy framework promotes legislation for waste recycling, encouraging the use of anaerobic digestion and composting technologies. While traditional wet anaerobic digestion still dominates large-scale organic waste treatment, small-scale anaerobic digestion (SSAD) has demonstrated significant potential for processing agricultural waste and organic sewage sludge. In Germany, for example, more than 560 small biogas plants have been established since 2016, generating an annual output of 271.3 GWh of electricity. This success is largely due to the Renewable Energy Act's Feed-in Tariff (FIT) policy, which provides subsidies for electricity produced by small biogas facilities [54]. In France, garage-type digesters are widely used for processing food waste and municipal wastewater in urban and suburban areas, while in

Italy, policy incentives support the development of biogas facilities to provide sustainable energy solutions for rural and local communities [55,56].

In the United States, upgrades to anaerobic digestion technology have focused on transforming wastewater treatment plants into water resource recovery facilities (WRRFs). Implementing real-time control for a 35% reduction in N_2O emissions, combined with electrolytic hydrogen production and pre-filtration technology, has enhanced organic matter collection efficiency and biogas production, thereby reducing reliance on fossil fuels [57]. Anaerobic digestion technology has also been effectively applied in large farms and slaughterhouses, leading to significant reductions in greenhouse gas emissions. For instance, large dairy farms have cut emissions by 2.45 to 3.52 million tonnes of CO_2-eq annually, with additional reductions achieved through cogeneration [58].

In Asia, particularly in China, anaerobic digestion technology has rapidly advanced under the impetus of the "dual carbon" policy. A successful example is seen in Weifang, Shandong Province, where biogas upgrading technology enables the conversion of 86,000 cubic meters out of 150,000 cubic meters of daily biogas production into biomethane for local use [59]. This biomethane, with chemical properties similar to natural gas, can be directly injected into the natural gas network, providing a pathway for the seamless integration of renewable energy with existing energy infrastructure. This approach not only reduces dependence on fossil fuels but also enhances energy security and supports decarbonization efforts. In the Nan'an community of Wuwei, Gansu Province, the central gas supply system maintains anaerobic digestion temperatures through biomass combustion, achieving a thermal efficiency of 86.5% [60]. In China, anaerobic digestion technology is transitioning from small-scale household applications to large-scale industrial systems, with significant contributions from large biogas plants expected to drive national biogas production by 2020 [61]. In this context, leveraging existing natural gas distribution networks for biomethane injection can facilitate efficient energy distribution, reduce greenhouse gas emissions, and establish a circular economy model that maximizes the value of organic waste. Simultaneously, it supports national energy and environmental goals, promoting sustainable development and resource efficiency.

Moreover, in other Asian countries like India, Nepal, and Vietnam, governments and NGOs are actively promoting household anaerobic digestion systems. In India, financial incentives and loans from the government enabled rural residents to install over 90,000 home-grade biogas digesters between 2017 and 2021, significantly improving rural sanitation [62]. In Indonesia, the implementation of decentralized wastewater treatment systems (DEWATS) combined with anaerobic digestion technology has successfully addressed weak wastewater treatment infrastructure, providing effective wastewater treatment and biogas production solutions to more than 15,000 communities [63].

Table 3. Case studies of anaerobic digestion technology development in different regions.

Region	Policy Support	Upgrade Status	Technology Application	Application Scenarios	References
Germany	Renewable Energy Law, small-scale electricity subsidy	Small-scale anaerobic digestion technology (SSAD)	Applied in agricultural waste treatment, supports agricultural economy	Agricultural waste treatment	[54]
France	Policy for small-scale biogas plant construction	Vehicle-scale digesters	Applied in urban organic waste for electricity and heat production	Urban organic waste treatment	[55]
Italy	2030 Biofuel Target	Biofuel technology	Processes organic waste, supports rural circular economy	Agricultural waste treatment	[56]
USA	WRRF facility transformation support	Transition to resource recovery facilities	Increases biogas yield, reduces GHG emissions	Large wastewater plants, landfill sites	[57,58,64]
China	Dual carbon policy	Industrial-scale development from small to large	Widespread biomass heating systems, increased gas contribution	Wastewater treatment, livestock waste management	[59–61]

Table 3. *Cont.*

Region	Policy Support	Upgrade Status	Technology Application	Application Scenarios	References
India	Government incentives and loans	Household-scale biogas systems	Household biogas plants improve rural sanitation	Agricultural and household waste treatment	[62]
Indonesia	Local government and NGO promotion	Decentralized wastewater treatment (DEWATS)	Reduction in organic pollutants, daily gas production over 20 m^3	Agricultural and residential areas	[63]
Nepal, Vietnam	NGO promotion of household biogas systems	Household-scale anaerobic digestion	Improved sanitation, supports agricultural resource recycling	Agricultural and household waste treatment	[62]
Brazil	Renewable Energy Law, National Solid Waste Policy	Large-scale landfill and co-digestion facilities	67% recycling rate with installed capacity of 835 MW, meeting 2.8% of national demand	Landfills, agricultural waste treatment	[65]
Chile	Policy support for traditional energy alternatives	Solid waste treatment technology	Reduce urban landfill emissions, supports energy recovery	Urban and agricultural waste treatment	[66]
Argentina	Decentralized renewable energy regulation	Co-digestion facilities	Annual generation of 6387 MWh, GHG emission reduction by 44.1–70.5%	Urban regions, electricity production	[67]

4. The Promoting Role of Anaerobic Digestion Technology in Circular Economy

4.1. Potential for Energy Self-Sufficiency and Carbon Reduction

Anaerobic digestion technology plays a crucial role in advancing the circular economy. As shown in Table 4, anaerobic digestion enables the conversion of sewage sludge into biogas, supports energy self-sufficiency through cogeneration, reduces dependence on fossil fuels, and facilitates the transformation of wastewater treatment plants into resource recovery facilities, thus lowering their carbon footprint. In Europe, policy support and technological advancements have positioned anaerobic digestion as a global leader in energy self-sufficiency and carbon reduction within wastewater treatment. For instance, Austria's Wolfgangsee-Ischl and Strass wastewater treatment plants produce 3 GWh of biogas annually using highly efficient combined heat and power (CHP) equipment, achieving complete energy self-sufficiency by 2008, with surplus electricity available for sale [68]. In Germany, the Grevesmühlen and Kohlbrandhoft wastewater treatment plants employed co-digestion technology to increase electricity production by 15% and generate a 20% energy surplus [69]. Additionally, Dutch dairy farms convert livestock manure and sewage sludge into energy through co-digestion and CHP systems, cutting their carbon footprint by 88–92% and reducing operational costs by 26% [70].

In the Americas, particularly in the United States, anaerobic digestion technology enables wastewater treatment plants to achieve energy self-sufficiency and recycle waste. For example, the East Bay Municipal Utility District (EBMUD) generates over $2 million annually from excess electricity produced through anaerobic digestion. At the Des Moines wastewater treatment plant, co-digestion technology has increased biogas production by 40%–50%, allowing for profitable biogas sales [71]. In Latin America, anaerobic digestion is widely applied on dairy farms, where it reduces greenhouse gas emissions by an estimated 32.8 million tonnes of CO_2-eq per year [72]. In Mexico, municipal wastewater treatment plants achieve 50%–60% energy self-sufficiency through anaerobic digestion, generating an annual output of 34 GWh of biogas [73].

In Asia, anaerobic digestion technology is aiding agriculture and livestock sectors in reducing environmental impacts and advancing the shift toward a circular economy. For example, in BB Nagar district, India, anaerobic digestion converts livestock and poultry waste into 10,637 kW of electricity, reducing CO_2 emissions by approximately 51,956.4 tonnes annually [74]. In China, 31 wastewater treatment plants in Guangzhou have achieved regional energy self-sufficiency, cutting electricity costs by 80%, reducing CO_2 emissions by

about 37.5 tonnes per day, and generating substantial benefits in the carbon trading market. By 2050, carbon credit revenues in the region are projected to reach 30 million yuan [75].

Table 4. Potential of anaerobic digestion technology in energy self-sufficiency and carbon reduction.

Region	Application Field	Energy Self-Sufficiency Potential	Carbon Reduction Capacity	Representative Case	Reference
Europe	Wastewater Treatment Plant	100% power self-sufficiency, over 10% surplus energy	Reduces CO_2 by over 10%	Wolfgangsee-Ischl WWTP, Austria	[68]
	Wastewater Treatment Plant	50.5% average energy recovery; 1.54 kWh per m^3 biogas	Reduces methane and N_2O emissions	Krosno WWTP, Poland	[76]
	Co-digestion	Electricity increases by 15%; 20% energy surplus	Reduces CO_2 emissions by 83–92%	Grevenmuehlen and Kohlbrand WWTP, Germany	[69]
	Dairy Farm	CHP systems achieve 100% energy self-sufficiency	Environmental impact reduced by 83–87%	Dutch dairy farm Annual cost savings of 26%	[70]
North America	Wastewater Treatment Plant	Surplus power generation generates 200 million USD annually	Significant carbon reduction	EBMUD WWTP, USA	[71]
	Co-digestion	Biogas yield increased by 40%; 50% biogas sold	Reduces methane and other GHGs	Des Moines WWTP, USA	[77]
	Dairy Farm	Energy self-sufficiency through bioenergy and heat recovery	60% reduction in methane and nitrous oxide emissions	Latin American dairy farm Annual reduction of 32.8 m tons of CO_2-eq	[72]
	Manure Processing	Over 20% energy surplus	Annual CO_2 reduction: 124 Mt	Annual reduction in Brazil agricultural waste about 12% of total emissions	[78]
	Municipal Wastewater Treatment Plant	Annual biogas production: 340 GWh	Reduces methane and CO_2 emissions	Mexico WWTP 50–60% energy self-sufficiency rate	[73]
Asia	Manure Processing	Power conversion over 1063 kW	Annual CO_2 reduction: 51,596 tons	BB Nagar, India Reduce dependence on fossil fuels	[74]
	Wastewater Treatment Plant	Daily biogas production: 390 kWh	Reduces GHG emissions from energy and fuel usage	Anaerobic digestion and photovoltaic system combination in South Korea Jeju Island WWTP	[79]
	Municipal Wastewater Treatment Plant	Electricity Cost reduction by 8%	Reduces 37.5 tons of CO_2-eq About 12.56% of total emissions	31 WWTP in Guangzhou, China Carbon markets generate revenue	[75]

4.2. Economic Role in Resource Recovery and Waste Management

As shown in Table 5, the contribution of anaerobic digestion technology to a circular economy is evident in its effective waste management and resource recycling capabilities [8,9,12]. By converting agricultural and livestock waste as well as sewage sludge into biogas and organic fertilizers [80–83], anaerobic digestion technology not only reduces the cost of traditional fertilizers but also enhances soil and environmental quality, supporting resource reuse [84]. Furthermore, processing digestate allows for the production of high-value materials, such as carbon-based compounds, nanofibers, and bio-oils, which find applications in energy storage and pollutant adsorption [85–87]. These materials not only improve economic efficiency but also foster sustainable development of the circular economy in sewage treatment and waste management.

In emerging economies, anaerobic digestion technology has shown substantial economic benefits, driving sustainable green economic growth. For instance, in Poland, approximately 34% and 30% of sludge are managed through agricultural applications and thermal conversion technologies, respectively [88]. Research indicates that sludge

gasification technology offers significant economic advantages within the circular economy, providing a net benefit of up to $3.5 million for small, decentralized wastewater treatment plants in Poland and reducing landfill costs. Additionally, the bio-oil generated through rapid sludge pyrolysis and the hydrogen yield during gasification, reaching 72.8–82.9%, further enhance energy recovery efficiency [89]. At the ZGO Gac plant in Poland, over 100,000 tonnes of solid waste are processed annually using anaerobic digestion and combined heat and power (CHP) systems, generating 6000 MWh of electricity—one-third of which is sold—resulting in a net surplus of €180,000. This demonstrates the critical role of anaerobic digestion technology in supporting the circular economy [90].

Since Croatia joined the European Union in 2013, it has introduced anaerobic digestion technology to treat municipal solid waste in order to meet EU waste management targets. The city of Zagreb collects about 270,000 tons of solid waste every year, of which 13.46% is converted into biogas through anaerobic digestion for power generation and heating, with an investment of 710,000 euros and an annual power generation income of about 1 million euros. At the same time, the cost of fertilizer is saved by about 500,000 euros per year [91]. In addition, the technology reduces greenhouse gas emissions by 43.59 tons of carbon dioxide equivalent per year [92], bringing Croatia a double advantage in terms of environmental and economic benefits. In Africa, despite slower overall economic and technological development, several rapidly urbanizing countries and regions have successfully implemented anaerobic digestion technology. For example, in South Africa's Western Cape Province, anaerobic digestion produces 100–150 m^3 of biogas per tonne of waste treated, reduces CO_2 emissions by 1 tonne, and enhances energy self-sufficiency [93]. In eThekwini, an anaerobic digestion project set to launch in 2027 aims to treat 13.1% of the city's total waste by 2035, potentially saving over R3.8 billion in treatment costs [94] and further advancing the circular economy.

In general, based on the analysis of anaerobic digestion technology adopted by various countries in Table 5, most countries achieve economic benefits through energy savings, waste conversion into electricity or biogas, and reductions in waste management costs. Additionally, many countries have successfully reduced GHG emissions and pollutants, contributing to sustainable development. In terms of resource recovery, the technology effectively transforms waste into valuable resources, thereby fostering a circular economy. The factors influencing these outcomes include the country's economic context, environmental policies, technological innovations, and energy demand. Developed countries and those with advanced infrastructure tend to reap higher economic and environmental benefits, which are further enhanced by supportive policies and technological advancements.

Table 5. The economic role of anaerobic digestion technology in resource recovery and waste management.

Region	Technology Application Type	Resource Recovery	Economic Benefits	Environmental Impact	Reference
Poland	Municipal Sludge Anaerobic Digestion	Hydrogen concentration 72.8–82.9%	Net income: USD 350,000 for small wastewater plants	Reduces sludge volume; 0.55–1.5% phosphorus recovery	[88–90]
	Municipal solid waste	Generates 6000 MWh of electricity; one-third sold	Annual revenue: USD 1.8 million	Provide organic fertilizer for agriculture, Reduce fertilizer costs, Reduce methane emissions	[90,95]
Mexico City	Biological pretreatment MBP	Consumes approx. 387 MJ fossil/Mg of energy	Annual savings of USD 207.6 in waste management costs	Reduces GHG emissions by 148 kg-CO_2e/Mg	[96]
Brazil	Two-Stage Membrane Bioreactor	Organic matter removal rate: 96.9%; methane concentration: 70.1%	Production increase: 25.7%, COD removal efficiency	Reduced water and soil pollution	[97]
USA	Waste Heat Energy Recovery	Recovers 20–30% of energy from waste heat	Annual savings on heating costs 20–30%	Reduce demand for fossil fuels, Reduce greenhouse gas emissions by 30%	[98]

Table 5. *Cont.*

Region	Technology Application Type	Resource Recovery	Economic Benefits	Environmental Impact	Reference
China	Food Waste Treatment	Biogas production: 130 m^3/ton	Annual revenue of RMB 20 million	Reduces solid waste by 46.8 kg CO_2-eq per ton	[99]
Norway	Reduces solid waste by 46.8 kg CO_2-eq per ton	Acid treatment for methane production; 42–50% yield	Reduces processing costs by 30%	Improves nutrient separation and reduces pollution	[100]
Germany	Municipal Solid Waste	100 kW waste-to-energy plant; 27.1 m^3 waste treated annually	Significant reductions in energy spending from fossil fuels	Reduces fossil fuel consumption by replacing 620 kg of CO_2-eq emissions	[101]
Croatia	Municipal Solid Waste	Annual electricity revenue: approx. EUR 1 million	Annual fertilizer cost savings: EUR 500,000	Reduces 43.59 tons CO_2 emissions; decreases reliance on agricultural fertilizers	[91,92]
South Africa	Municipal Waste Treatment	100–150 million m^3 annual biogas production	Estimated savings of ZAR 3.8 billion by 2035	Reduces 1 ton of CO_2 emissions; decreases reliance on traditional energy sources	[93,94]

5. The Development Trend of Anaerobic Digestion Technology

5.1. Emerging Technologies and Intelligent Applications

Anaerobic digestion technology is evolving alongside advancements in science and technology. As shown in Table 6, new processes such as temperature-phased anaerobic digestion (TPAD) and autogenic high-pressure digestion (AHPD) significantly boost biogas production and methane concentration [102,103]. Additionally, the implementation of forward transport membrane (FTM) technology and microalgae CO_2 capture has proven effective in enhancing methane purity and yield [69,104]. Pretreatment technologies, including wet oxidation and steam explosion, greatly improve the biodegradability of lignocellulosic materials [105], while low-temperature condensation enables the co-production of high-purity methane and carbon dioxide [106]. Furthermore, integrating anaerobic digestion with biorefinery technologies allows for the conversion of organic biomass into a diverse range of green energy and chemical products [107].

Digital and intelligent technologies have significantly advanced wastewater treatment, particularly in anaerobic digestion, enhancing both process accuracy and efficiency [108]. Artificial neural networks (ANN) and machine learning algorithms, such as random forests and support vector machines (SVM), optimize biogas production and facilitate predictive maintenance, achieving efficiency gains of up to 15% [109,110]. Additionally, the use of fuzzy logic systems and Internet of Things (IoT) technologies optimizes feeding systems and equipment maintenance, further improving overall operational efficiency [111,112]. The integration of life cycle assessment (LCA) tools has led to a 20–30% reduction in greenhouse gas emissions from wastewater treatment plants [113], providing substantial support for sustainable development.

Overall, the integration of artificial intelligence (AI) and the Internet of Things (IoT) enhances decision-making capabilities through advanced data analysis and automated systems, enabling operators to dynamically adjust feeding strategies and proactively resolve inefficiencies. This integration also minimizes downtime and maintenance costs, significantly improving operational performance. Collectively, these technologies provide transformative potential for predictive maintenance and process optimization, enhancing the efficiency and reliability of anaerobic digestion systems while aligning with the objectives of the circular economy.

Table 6. Development of anaerobic digestion technology in emerging technologies and intelligent applications.

Application Field	Technology Type	Key Performance Indicators	Application Scenarios	Technical Challenges	Reference
Energy Production	Temperature Phased Anaerobic Digestion (TPAD)	Methane yield increase of 9.6%	Various organic waste	Complex temperature control, energy demand	[102]
	Self-pressurized Gasification	Methane purity up to 82%, low-grade heat utilization	Various gasification reactors	High equipment manufacturing cost, complex pressure control	[103]
Methane Enrichment	Membrane Transport Enhancement	Improved methane purity	Biogas upgrading systems	High cost of nanoporous membrane materials	[104]
Methane Yield Increase	Microalgae Cultivation with CO_2	Methane yield up to 92%, removes ammonia	Waste treatment facilities	Nutrient demand additional environmental control	[69]
Agricultural Waste Treatment	Steam Explosion Pretreatment	Enhanced methane production	Agricultural and organic fertilizers	High equipment cost, complex pretreatment process	[105]
Wastewater and Sludge Treatment	Low-Temperature Liquefaction	Methane purity up to 99%	Wastewater treatment plants	Requires large-scale cooling infrastructure	[106]
Biomass Resource Utilization	Bio-refining and Anaerobic Digestion Integration	Comprehensive production of ethanol, bio-oil, syngas	Agricultural waste (e.g., sugarcane)	Complex industrial processes, high energy input	[107]
Process Control and Monitoring	Artificial Neural Networks (ANN)	Production efficiency increase by 20%	Biogas production systems	High sensor demand, complex model training	[110]
Optimization Maintenance and Prediction	SVM and Random Forest	Biogas yield increase of 15%, reduced maintenance costs	Large biogas plants	Requires extensive historical data for training	[109]
Biogas Yield Prediction	Random Forest Algorithm	Optimized biogas production forecast	Large biogas plants	High computational complexity, increased reliability	[110]
Feed System Optimization	Fuzzy Logic	Biogas yield increase of 10%, reduced labor dependency	Various biogas production systems	Complex algorithm adjustments, high transmission accuracy requirement	[111]
Life Cycle Assessment	Integrated LCA Model	30% reduction in GHG emissions, improved resource utilization	Wastewater treatment plants	Complex data model construction, extensive data collection time	[113]
Remote Monitoring and Maintenance	Internet of Things IoT	Enhanced data centralization, increased efficiency and operational rate	Large biogas plants, remote facility management	High system setup cost, need for continuous maintenance updates	[112]

5.2. Policy and Market Drivers Factors

Figure 3 illustrates the main evolution of the European biogas industry from 2020 to 2050, highlighting a gradual shift toward biomethane production and carbon appreciation. This evolution underscores the rapid development of anaerobic digestion technology, propelled by both policy and market forces. On the policy front, governments have introduced incentives to encourage the adoption and expansion of this technology. For instance, the European Green Deal and the EU's Long-Term Climate Strategy emphasize enhancing resource efficiency and promoting a circular economy through anaerobic digestion [114]. EU waste management policies, including the Landfill Directive and the Waste Framework Directive, also support anaerobic digestion's role in reducing landfill use and pollutant emissions [115].

Specific national policies have further spurred market growth. In France, the Energy Transition Act and the Multi-Annual Energy Plan have strengthened the biogas sector, aiming for biogas to comprise 30% of natural gas consumption by 2030 [116]. In Sweden,

the Climate Investment Program promotes the biogas market with the goal of making the transport system fossil-fuel-free by 2030 [117]. Similarly, in Brazil, the Biogas and Biomethane State Policy outlines the rights and obligations of stakeholders, fostering greater market integration [118].

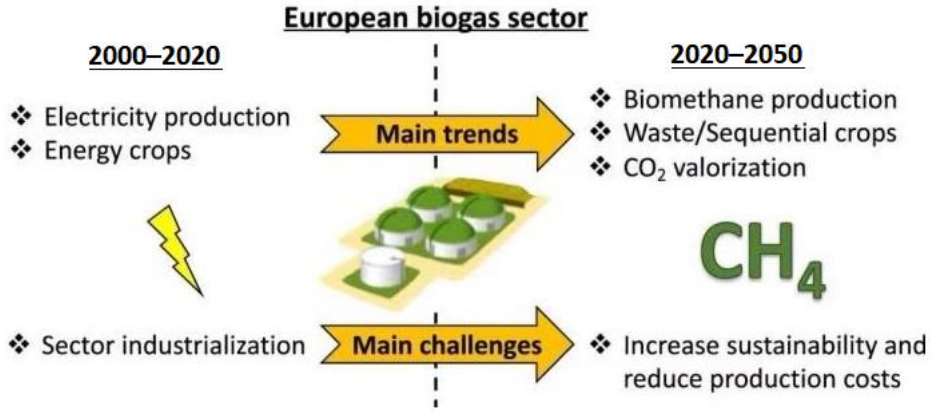


Figure 3. Development trend of European biogas industry 2000–2050 [114].

Market drivers are also accelerating the advancement of anaerobic digestion technologies. In Poland, rising global grain prices have led operators to shift towards using food industry and municipal waste as feedstocks, thereby enhancing economic efficiency and reducing competition with food resources [119]. In the Czech Republic, biofuel use is encouraged through subsidies and tax incentives [120]. In China, abundant supplies of livestock manure and crop residues serve as substantial feedstocks for anaerobic digestion, with large-scale biomethane and biogas projects expected to deliver significant economic benefits [43]. Together, these policy and market factors have fostered a supportive environment for the growth of anaerobic digestion technology, advancing resource recovery and the circular economy.

6. Challenges and Obstacles

6.1. Technical Bottlenecks and Economic Feasibility Challenges

Anaerobic digestion technology faces several technical and economic challenges in practical applications. As shown in Table 7, on the technical side, high ammonia nitrogen concentrations and volatile fatty acid accumulation can inhibit microbial activity, adversely affecting methane production [121]. While mature ammonia removal technologies exist, nitrogen and phosphorus recovery efficiencies remain below optimal levels, and the use of membrane technologies is constrained by clogging issues [122]. Additionally, untreated high concentrations of ammonia nitrogen and heavy metals can lead to environmental pollution, limiting the feasibility of agricultural applications [123]. Generally, the main technical challenge faced by anaerobic digestion technology in practical application is generally the environmental pollution and blockage caused by the immaturity of various technologies.

At the economic level, the high costs of nutrient recovery and raw material pretreatment add to operational expenses [123–127]. Although two-stage anaerobic digestion can enhance energy recovery, it requires additional equipment and energy input, increasing costs [128]. Furthermore, low market demand for biogas persists due to the competitive pricing of traditional fertilizers and fossil fuels, limiting commercial expansion [129]. Therefore, the main economic challenges encountered in the application process of anaerobic digestion technology include an increase in costs and a decrease in demand. Instability in methane production also directly affects economic viability, with reduced gas yields leading to lower energy recovery [130]. Existing subsidy policies primarily support project construction but lack operational subsidies, making it challenging for some biogas projects to maintain profitability [131], which is an additional significant concern that cannot be overlooked.

Additionally, the challenges encountered by different countries in the application of anaerobic digestion technology vary based on their technological development, economic conditions, and policy environment. Developed countries generally face fewer challenges related to equipment and technology maintenance; however, they still struggle with marketing difficulties and the lack of operational subsidies, largely due to the competitive pricing of fossil fuels and insufficient market demand for green energy. In contrast, developing countries face more severe technical challenges, such as membrane fouling and lower ammonia nitrogen recovery efficiency, while the high costs associated with pretreatment and dual-stage systems exacerbate the economic burden. For countries with significant agricultural needs, there is a heightened focus on mitigating the environmental issues caused by nitrogen and heavy metal pollution, which directly impact soil health and agricultural productivity. Overall, the performance of technological and economic challenges varies considerably across countries, shaped by a combination of national infrastructure, economic development levels, and policy support.

Table 7. The technical bottleneck and economic feasibility challenge of anaerobic digestion.

Field	Technical/Economic Category	Challenges	Impact	Solutions	Reference
Technical Challenges	Substrate Processing Efficiency, pH Value Control	Excessive ammonia concentration, accumulation of volatile fatty acids	Reduced gas yield, unstable fermentation process	Optimize substrate ratio, adjust pH of feedstock	[121]
	Nitrogen and phosphorus recovery technology	Membrane separation process Fouling problem	Reduced membrane lifespan, increased operational maintenance costs	Develop fouling-resistant membrane materials, enhance cleaning efficiency	[122]
	Ammonia recovery technology	Low maturity of membrane contactor technology	Increased operational and management complexity, higher system maintenance costs	Enhance membrane contactor, implement automatic control	[132]
	Environmental Impact Control	Untreated Nitrogen and Heavy Metals, Environmental and soil pollution	Soil degradation, impact on agriculture and environment	Improve nitrogen recovery efficiency, enhance heavy metal recovery technologies	[123]
Economic Challenges	Pretreatment Costs	High time and equipment investment in pretreatment process	Increased operational costs	Optimize pretreatment techniques, reduce equipment investment	[125]
	Dual-Stage System Costs	High costs for dual-stage gasification and energy system	System costs and energy consumption increase, Reduce in economic efficiency	Increase single-stage system efficiency, reduce equipment costs	[128]
	Methane Yield Instability	Fluctuating methane yield impacts economic benefits	Unstable system energy recovery, Reduced economic efficiency	Develop stable microbial agents, optimize operating conditions	[130]
	Market Promotion Difficulty	Immature bio-fertilizer and biofuel market; insufficient demand	Hindered commercial promotion of green fuels	Increase policy support, promote green fuel applications	[129]
	Lack of Operational Subsidies	Existing subsidy policies lack long-term support	Reduced economic viability, difficult to maintain operations	Government to increase long-term operational subsidies	[131]

6.2. Regulatory Challenges and Public Acceptance Issues

In terms of policy and regulation, regulatory differences in the application of anaerobic digestion technology in different countries limit the uniform implementation of the technology and affect the efficiency of cross-border trade and digestion management. While

Germany and the United Kingdom have developed standards (such as PAS-110) to regulate heavy metals and organic pollutants in digesters, many countries still lack similar regulations, which may limit the use of digesters as agricultural fertilizers [133]. In addition, the lack of global harmonized digestion regulations makes cross-border agricultural trade challenging. For example, EU restrictions on mechanically separated organic waste may not apply to other countries, affecting international trade in digestives [134]. Despite the potential environmental and economic benefits of anaerobic digestion in agriculture, the impact on the environment and human health needs to be supported by more research. Currently, the tools used to assess digestive risk (such as life cycle assessment and ecological risk assessment) are not widely available in many countries, which affects government and industry assessments of the quality and safety of disinfectants [36]. At the same time, as shown in Figure 4, as anaerobic digestion is an emerging technology, the EU has adopted the process of formulating policies through expert opinions, evidence review and scientific suggestions, which shows that the multi-layered regulatory system leads to poor information transmission, especially the lack of coordination among government departments, resulting in inefficient policy implementation [135].

In terms of public acceptance, limited awareness of anaerobic digestion technology often leads to concerns about the composition and safety of residual compounds [136]. Project size can also influence acceptance, with smaller facilities generally gaining easier support, whereas larger projects may encounter resistance due to external investment involvement and potential impacts on the local area [137]. Additionally, the "NIMBY" (Not in My Backyard) effect is particularly notable in the construction of large anaerobic digestion facilities. While the public may broadly support renewable energy, there is often opposition to facilities being located close to residential areas [138]. For instance, in Germany, the clustered construction of anaerobic digestion facilities has sometimes met with resident opposition. Conversely, in France, despite facility visibility, some residents perceive these installations as compatible with the rural landscape, making them more accepting.

In summary, the key to overcoming the "NIMBY" effect lies in enhancing community engagement and transparency by involving the public in decision-making from the early stages of the project and providing regular updates to build trust. Simultaneously, educational and outreach efforts should be undertaken to comprehensively communicate the environmental and economic benefits of anaerobic digestion facilities. Additionally, optimizing facility siting and design, such as incorporating greenery or adopting inconspicuous designs, can help minimize visual and environmental impacts. Providing economic incentives, such as sharing project revenues or offering free organic fertilizers to the local community, further ensures direct benefits to residents, fostering greater acceptance and support for the project.

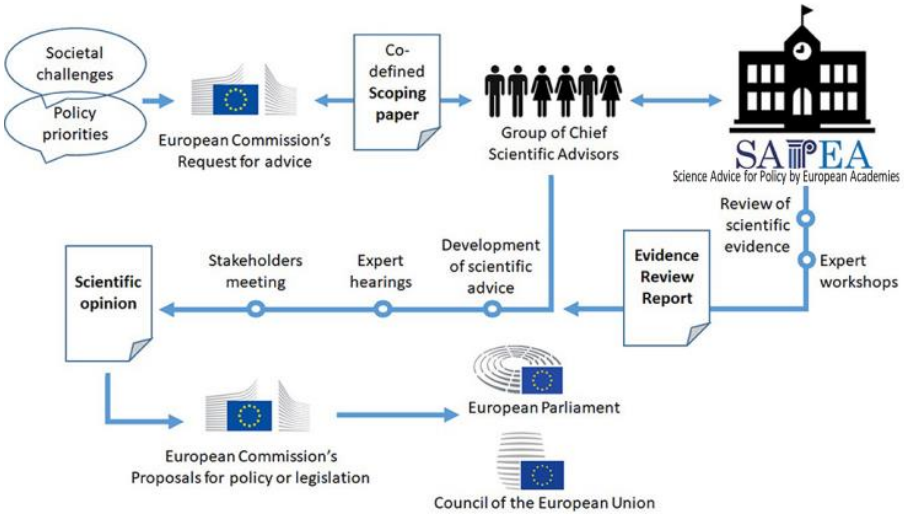


Figure 4. EU policy formulation and proposed adoption path [139].

7. Conclusions and Prospects

This review systematically examines the application of anaerobic digestion technology in wastewater treatment and its role in promoting the circular economy. As a sustainable approach for converting organic waste into biogas and organic fertilizers, anaerobic digestion holds significant potential to reduce emissions and energy consumption while enhancing energy self-sufficiency and resource recycling in wastewater treatment plants, thus becoming a key strategy in achieving the "dual carbon" goal. Although technology is relatively mature in developed regions, developing countries continue to face challenges related to limited financial and technical support; nonetheless, anaerobic digestion technology demonstrates broad prospects for growth.

Against the backdrop of the "dual carbon" goal, the future of anaerobic digestion technology presents both opportunities and challenges. Driven by climate policies and the imperative to reduce carbon emissions, advancements in co-digestion, multi-stage anaerobic digestion, and intelligent control methods promise to enhance efficiency and economic benefits. Policy incentives and market forces are also accelerating technological progress, with biogas markets and carbon trading systems improving economic viability. However, technical challenges remain, including digestate treatment, ammonia nitrogen inhibition, and volatile fatty acid accumulation, as well as the challenge of balancing capital investment with financial returns. Future research should prioritize improving technological stability, reducing costs, and refining policy support. Increasing public awareness of environmental protection and fostering social acceptance of anaerobic digestion projects are also crucial.

In conclusion, as a vital technology for promoting the circular economy and green development, anaerobic digestion will play an essential role in the global energy transition and in achieving carbon neutrality. Policymakers should advance supportive policies, standardization, and international cooperation, while the wastewater treatment industry must focus on technology integration and intelligent systems to achieve the Sustainable Development Goals.

Funding: This research received no external funding.

Data Availability Statement: Data sharing not applicable.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Moyer, J.; Hedden, S. Are we on the right path to achieve the sustainable development goals? *World Dev.* **2020**, *127*, 104749. [CrossRef]
2. Liu, W.; McKibbin, W.J.; Morris, A.C.; Wilcoxen, P.J. Global economic and environmental outcomes of the Paris Agreement. *Energy Econ.* **2020**, *90*, 104838. [CrossRef]
3. Zhou, S.; Tong, Q.; Pan, X.; Cao, M.; Wang, H.; Gao, J.; Ou, X. Research on low-carbon energy transformation of China necessary to achieve the Paris agreement goals: A global perspective. *Energy Econ.* **2021**, *95*, 105137. [CrossRef]
4. Zhang, S.; Chen, W. China's energy transition pathway in a carbon neutral vision. *Engineering* **2021**, *14*, 64–76. [CrossRef]
5. Maktabifard, M.; Hazmi, A.H.; Szulc, P.; Mousavizadegan, M.; Xu, X.; Zaborowska, E.; Li, X.; Mąkinia, J. Net-zero carbon condition in wastewater treatment plants: A systematic review of mitigation strategies and challenges. *Renew. Sustain. Energy Rev.* **2023**, *185*, 113638. [CrossRef]
6. Ren, Z.Y.; Schnoor, J.; Pagilla, K. *Toward a Net Zero Circular Water Economy*; IWA Publishing: London, UK, 2022; Volume 1, pp. 1–13.
7. Nabaterega, R.; Kumar, V.; Khoei, S.; Eskicioglu, C. A review on two-stage anaerobic digestion options for optimizing municipal wastewater sludge treatment process. *J. Environ. Chem. Eng.* **2021**, *9*, 105502. [CrossRef]
8. He, X.M.; Zhang, T.; Ren, H.Q.; Li, G.X.; Ding, L.L.; Pawlowski, L. Phosphorus recovery from biogas slurry by ultrasound/H_2O_2 digestion coupled with HFO/biochar adsorption process. *Waste Manag.* **2017**, *60*, 219–229. [CrossRef]
9. Zhang, T.; Wu, X.S.; Shaheen, S.M.; Zhao, Q.; Liu, X.J.; Rinklebe, J.; Ren, H.Q. Ammonium nitrogen recovery from digestate by hydrothermal pretreatment followed by activated hydrochar sorption. *Chem. Eng. J.* **2020**, *379*, 122254. [CrossRef]
10. Velenturf, A.; Purnell, P. Principles for a sustainable circular economy. *Sustain. Prod. Consum.* **2021**, *27*, 1437–1457. [CrossRef]
11. Barros, M.; Salvador, R.; Prado, F.G.; Francisco, C.A.; Piekarski, C.M. Circular economy as a driver to sustainable businesses. *Clean. Environ. Syst.* **2020**, *2*, 100006. [CrossRef]

12. Xu, Q.; Zhang, T.; Niu, Y.Q.; Mukherjee, S.; Elwafa, A.S.F.; Nguyen, N.S.H.; Aboud, A.N.M.; Wang, Y.K.; Pu, M.J.; Zhang, Y.R.; et al. 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.* **2024**, *942*, 173567. [CrossRef] [PubMed]
13. Liu, G.; Xu, Q.; Elwafa, A.S.F.; Alshehri, A.M.; Zhang, T. Hydrothermal carbonization technology for wastewater treatment under the "dual carbon" goals: Current status, trends, and challenges. *Water* **2024**, *16*, 1749. [CrossRef]
14. Ali, F.; Ali, N.; Ahmad, I.; Khurshid, R.; Javed, M.; Mulla, S.; Bilal, M.; Iqbal, H.M.N. *Sustainable Management of Municipal Solid Waste to Fuel: An Overview for a Better Tomorrow*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 2, pp. 289–314.
15. Sanaye, S.; Mohammadi, M.; Yazdani, M.; Rashvanlou, R.B. Bio-gas augmentation and waste minimization by co-digestion process in anaerobic digestion system of a municipal waste water treatment plant. *Energy Convers. Manag.* **2022**, *268*, 115989. [CrossRef]
16. Başţabak, B.; Koçar, G. A review of the biogas digestate in agricultural framework. *J. Mater. Cycles Waste Manag.* **2020**, *22*, 1318–1327. [CrossRef]
17. Niemiec, M.; Sikora, J.; Sikora, S.A.; Szostak, G.Z.; Komorowska, M. Assessment of the Possibilities for the Use of Selected Waste in Terms of Biogas Yield and Further Use of Its Digestate in Agriculture. *J. Mater.* **2022**, *15*, 988. [CrossRef] [PubMed]
18. Barampouti, E.M.; Mai, S.; Malamis, D.; Moustakas, K.; Loizidou, M. Exploring technological alternatives of nutrient recovery from digestate as a secondary resource. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110379. [CrossRef]
19. Ngo, T.; Ball, A.S.; Shahsavari, E. The current status, potential benefits and future prospects of the Australian biogas sector. *J. Sustain. Bioenergy Syst.* **2021**, *11*, 14–32. [CrossRef]
20. Uddin, M.; Wright, M. Anaerobic digestion fundamentals, challenges, and technological advances. *Phys. Sci. Rev.* **2022**, *8*, 2819–2837. [CrossRef]
21. Kunatsa, T.; Xia, X. A review on anaerobic digestion with focus on the role of biomass co-digestion, modelling and optimisation on biogas production and enhancement. *Bioresour. Technol.* **2021**, *344*, 126311. [CrossRef] [PubMed]
22. Roopnarain, A.; Rama, H.; Ndaba, B.; Bello-Akinosho, M.; Bamuza-Pemu, E.; Adeleke, R. Unravelling the anaerobic digestion 'black box': Biotechnological approaches for process optimization. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111717. [CrossRef]
23. Ampese, L.; Sganzerla, W.; Ziero, D.D.H.; Mudhoo, A.; Martins, G.; Carneiro, F.T. Research progress, trends, and updates on anaerobic digestion technology: A bibliometric analysis. *J. Clean. Prod.* **2022**, *331*, 130004. [CrossRef]
24. Yang, X.; Liu, Y.; Thrän, D.; Bezama, A.; Wang, M. Effects of the German renewable energy sources act and environmental, social and economic factors on biogas plant adoption and agricultural land use change. *Energy Sustain. Soc.* **2021**, *11*, 6. [CrossRef]
25. Grando, L.R.; Antune, S.A.M.; Fonseca, F.V.; Sánchez, A.; Barrena, R.; Font, X. Technology overview of biogas production in anaerobic digestion plants: A European evaluation of research and development. *Renew. Sustain. Energy Rev.* **2017**, *80*, 44–53. [CrossRef]
26. Shrestha, B.; Hernandez, R.; Fortela, D.; Sharp, W.; Chistoserdov, A.; Gang, D.; Revellame, E.; Holmes, W.; Zappi, M. A review of pretreatment methods to enhance solids reduction during anaerobic digestion of municipal wastewater sludges and the resulting digester performance: Implications to future urban biorefineries. *Appl. Sci.* **2020**, *10*, 9141. [CrossRef]
27. Hanum, F.; Yuan, L.C.; Kamahara, H.; Aziz, H.A.; Atsuta, Y.; Yamada, T.; Daimon, H. Treatment of sewage sludge using anaerobic digestion in Malaysia: Current state and challenges. *Front. Energy Res.* **2019**, *7*, 19. [CrossRef]
28. Roopnarain, A.; Adeleke, R. Current status, hurdles and future prospects of biogas digestion technology in Africa. *Renew. Sustain. Energy Rev.* **2017**, *67*, 1162–1179. [CrossRef]
29. Correa, V.J.; Manandhar, A.; Shah, A. Economic Implications of Anaerobic Digestion for Bioenergy Production and Waste Management. Available online: https://ohioline.osu.edu/factsheet/fabe-6611 (accessed on 20 August 2024).
30. Subbarao, P.; D'Silva, T.; Adlak, K.; Kumar, S.; Chandra, R.; Vijay, V. Anaerobic digestion as a sustainable technology for efficiently utilizing biomass in the context of carbon neutrality and circular economy. *Environ. Res.* **2023**, *234*, 116286. [CrossRef]
31. Liu, C.; Moon, D.; Watabe, A. Assessing the economic and environmental impacts of anaerobic digestion for municipal organic waste: A case study of Minamisanriku Town, Japan. *Sustainability* **2024**, *16*, 6793. [CrossRef]
32. Kiselev, A.; Magaril, E.; Giurea, R. Environmental and economic forecast of the widespread use of anaerobic digestion techniques. *Recycling* **2024**, *9*, 62. [CrossRef]
33. Huang, W.; Fooladi, H. Economic and environmental estimated assessment of power production from municipal solid waste using anaerobic digestion and landfill gas technologies. *Energy Rep.* **2021**, *7*, 4460–4469. [CrossRef]
34. Li, Y.; Qi, C.; Zhang, Y.; Li, Y.; Wang, Y.; Li, G.; Luo, W. Anaerobic digestion of agricultural wastes from liquid to solid state: Performance and environ-economic comparison. *Bioresour. Technol.* **2021**, *332*, 125080. [CrossRef] [PubMed]
35. Chowdhury, T.H. Technical-economical analysis of anaerobic digestion process to produce clean energy. *Energy Rep.* **2021**, *7*, 247–253. [CrossRef]
36. Lamolinara, B.; Pérez-Martínez, A.; Guardado-Yordi, E.; Fiallos, C.G.; Diéguez-Santana, K.; Ruiz-Mercado, G.J. Anaerobic digestate management, environmental impacts, and techno-economic challenges. *Waste Manag.* **2022**, *140*, 14–30. [CrossRef]
37. Arias, A.; Feijoo, G.; Moreira, T.M. What is the best scale for implementing anaerobic digestion according to environmental and economic indicators? *J. Water Process Eng.* **2020**, *35*, 101235. [CrossRef]
38. Zhuang, Z.; Mohamed, B.A.; Li, L.Y.; Swei, O. An economic and global warming impact assessment of common sewage sludge treatment processes in North America. *J. Clean. Prod.* **2022**, *370*, 133539. [CrossRef]

39. Balcioglu, G.; Jeswani, H.K.; Azapagic, A. Evaluating the environmental and economic sustainability of energy from anaerobic digestion of different feedstocks in Turkey. *Sustain. Prod. Consum.* **2022**, *32*, 924–941. [CrossRef]
40. Patiño, A.T.; Sánchez, O.M.; Ariel, C. Prefeasibility analysis of different anaerobic digestion upgrading pathways using organic kitchen food waste as raw material. *J. Ferment.* **2024**, *10*, 300. [CrossRef]
41. Rajendran, K.; Mahapatra, D.; Venkatraman, A.; Muthuswamy, S.; Pugazhendhi, A. Advancing anaerobic digestion through two-stage processes: Current developments and future trends. *Renew. Sustain. Energy Rev.* **2020**, *123*, 109746. [CrossRef]
42. Iglesias, R.; Muñoz, R.; Polanco, M.; Díaz, I.; Susmozas, A.; Moreno, A.D.; Guirado, M.; Carreras, N.; Ballesteros, M. Biogas from anaerobic digestion as an energy vector: Current upgrading development. *Energies* **2021**, *14*, 2742. [CrossRef]
43. Zhao, J.; Li, Y.; Dong, R. Recent progress towards in-situ biogas upgrading technologies. *Sci. Total Environ.* **2021**, *800*, 149667. [CrossRef]
44. Nath, D.; Chakraborty, I.; Ghangrekar, M.M. Integrating microbial electrochemical technologies for methane-to-bioelectricity and water-splitting to impart self-sustainability to wastewater treatment plants. *Bioresour. Technol. Rep.* **2021**, *13*, 100644. [CrossRef]
45. Zhu, X.; Leininger, A.; Jassby, D.; Tsesmetzis, N.; Ren, J.Z.Y. Will membranes break barriers on volatile fatty acid recovery from anaerobic digestion? *ACS EST Eng.* **2020**, *1*, 141–153. [CrossRef]
46. Vinardell, S.; Astals, S.; Peces, M.; Cardete, M.; Fernández, I.; Alvarez, M.J.; Dosta, J. Advances in anaerobic membrane bioreactor technology for municipal wastewater treatment: A 2020 updated review. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109936. [CrossRef]
47. Masebinu, S.; Akinlabi, E.; Muzenda, E.; Aboyade, A. A review of biochar properties and their roles in mitigating challenges with anaerobic digestion. *Renew. Sustain. Energy Rev.* **2019**, *103*, 291–307. [CrossRef]
48. D'Silva, C.T.; Isha, A.; Chandra, R.; Vijay, K.V.; Subbarao, P.M.V.; Kumar, R.; Chaudhary, P.V.; Singh, H.; Khan, A.; Tyagi, K.V.; et al. Enhancing methane production in anaerobic digestion through hydrogen assisted pathways—A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111536. [CrossRef]
49. Jensen, M.; Jensen, B.; Ottosen, L.; Kofoed, M. Integrating H_2 injection and reactor mixing for low-cost H_2 gas-liquid mass transfer in full-scale in situ biomethanation. *Biochem. Eng. J.* **2021**, *166*, 107869. [CrossRef]
50. Chen, D.; Yin, D.; Liu, W.; Lan, W.; Wang, Y. Anaerobic co-digestion scheme of biogas engineering based on feedstock and temperature. *BioResources* **2023**, *18*, 5777–5797. [CrossRef]
51. Yao, Y.; Huang, G.; An, C.; Chen, X.; Zhang, P.; Xin, X.; Shen, J.; Agnew, J. Anaerobic digestion of livestock manure in cold regions: Technological advancements and global impacts. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109494. [CrossRef]
52. Karki, R.; Chuenchart, W.; Surendra, K.C.; Shrestha, S.; Raskin, L.; Sung, S.; Hashimoto, A.; Khanal, K.S. Anaerobic co-digestion: Current status and perspectives. *Bioresour. Technol.* **2021**, *330*, 125001. [CrossRef]
53. Cucina, M. Integrating anaerobic digestion and composting to boost energy and material recovery from organic wastes in the circular economy framework in Europe: A review. *Bioresour. Technol. Rep.* **2023**, *24*, 101642. [CrossRef]
54. O'Connor, S.; Ehimen, E.; Pillai, S.; Black, A.; Tormey, D.; Bartlett, J. Biogas production from small-scale anaerobic digestion plants on European farms. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110580. [CrossRef]
55. Adami, L.; Schiavon, M.; Torretta, V.; Costa, L.; Rada, E. Evaluation of conventional and alternative anaerobic digestion technologies for applications to small and rural communities. *Waste Manag.* **2020**, *118*, 79–89. [CrossRef] [PubMed]
56. Hussain, Z.; Mishra, J.; Vanacore, E. Waste to energy and circular economy: The case of anaerobic digestion. *J. Enterp. Inf. Manag.* **2020**, *33*, 817–838. [CrossRef]
57. Faragò, M.; Damgaard, A.; Madsen, J.A.; Andersen, J.K.; Thornberg, D.; Andersen, M.H.; Rygaard, M. From wastewater treatment to water resource recovery: Environmental and economic impacts of full-scale implementation. *Water Res.* **2021**, *204*, 117554. [CrossRef]
58. Greene, J.M.; Wallace, J.; Williams, R.B.; Leytem, A.B.; Bock, B.R.; McCully, M.; Kaffka, S.R.; Rotz, A.C.; Quinn, J.C. National greenhouse gas emission reduction potential from adopting anaerobic digestion on large-scale dairy farms in the United States. *Environ. Sci. Technol.* **2024**, *58*, 12409–12419. [CrossRef] [PubMed]
59. Lu, J.; Gao, X. Biogas: Potential, challenges, and perspectives in a changing China. *Biomass Bioenergy* **2021**, *150*, 106127. [CrossRef]
60. Li, J.; Gan, C.; Zhou, J.; Novakovic, V. Performance analysis of biomass direct combustion heating and centralized biogas supply system for rural districts in China. *Energy Convers. Manag.* **2023**, *278*, 116730. [CrossRef]
61. Obileke, K.; Nwokolo, N.; Makaka, G.; Mukumba, P.; Onyeaka, H. Anaerobic digestion: Technology for biogas production as a source of renewable energy—A review. *Energy Environ.* **2020**, *32*, 191–225. [CrossRef]
62. Almansa, X.F.; Starostka, R.; Raskin, L.; Zeeman, G.; De Los Reyes, F., III; Waechter, J.; Yeh, D.; Radu, T. Anaerobic digestion as a core technology in addressing the global sanitation crisis: Challenges and opportunities. *Environ. Sci. Technol.* **2023**, *57*, 19078. [CrossRef] [PubMed]
63. Widyarani, D.R.; Hamidah, U.; Komarulzaman, A.; Rosmalina, R.T.; Sintawardani, N. Domestic wastewater in Indonesia: Generation, characteristics and treatment. *Environ. Sci. Pollut. Res.* **2022**, *29*, 32397–32414. [CrossRef]
64. Wang, S.; Sahoo, K.; Jena, U.; Dong, H.; Bergman, R.; Runge, T. Life-cycle assessment of treating slaughterhouse waste using anaerobic digestion systems. *J. Clean. Prod.* **2021**, *292*, 126038. [CrossRef]
65. Costa, J.M.; Beatriz, A.; Flavia, A.; Damasceno, B.; Duran, K.A.; Jerônimo, K.A.; Silva, M.M.; Cristina, T.; Rodriguez, R.P. Environmental aspects and perspectives of the Brazilian market for biogas and biomethane from anaerobic digestion: A review. *Bioenergy Res.* **2023**, *17*, 59–72. [CrossRef]

66. Vega, L.; Bautista, K.; Campos, H.; Daza, S.; Vargas, G. Biofuel production in Latin America: A review for Argentina, Brazil, Mexico, Chile, Costa Rica and Colombia. *Energy Rep.* **2024**, *11*, 28–38. [CrossRef]
67. Benito, A.; Verdezoto, C.P.; Burlot, A.; Arena, A. Hybrid power system for distributed energy deploying biogas from municipal solid waste and photovoltaic solar energy in Mendoza, Argentina. *E3S Web Conf.* **2024**, *532*, 01001. [CrossRef]
68. Tauber, J.; Ramsbacher, A.; Svardal, K.; Krampe, J. Energetic potential for biological methanation in anaerobic sewage sludge digesters in Austria. *Energies* **2021**, *14*, 6618. [CrossRef]
69. Nguyen, L.; Kumar, J.; Vu, M.; Mohammed, J.; Pathak, N.; Commault, A.; Sutherland, D.; Zdarta, J.; Tyagi, V.; Nghiem, L. Biomethane production from anaerobic co-digestion at wastewater treatment plants: A critical review on development and innovations in biogas upgrading techniques. *Sci. Total Environ.* **2020**, *765*, 142753. [CrossRef]
70. Middelburg, T. Achieving Energy Self-Sufficiency and Circularity in the Dutch Agricultural Sector, Using Anaerobic Digestion. Master's Thesis, University of Groningen, Groningen, The Netherlands, 2020.
71. Lima, D.; Appleby, G.; Li, L. A scoping review of options for increasing biogas production from sewage sludge: Challenges and opportunities for enhancing energy self-sufficiency in wastewater treatment plants. *Energies* **2023**, *16*, 2369. [CrossRef]
72. Schneider, V.J.; Isaksson, H.L.; Mainali, B.; Herrero, M.J.; Cardozo, E.; Malmquist, A.; Martin, A. Energy self-sufficiency and greenhouse gas emission reductions in Latin American dairy farms through massive implementation of biogas-based solutions. *Energy Convers. Manag.* **2022**, *261*, 115670. [CrossRef]
73. Paredes, M.; Güereca, L.; Molina, L.; Noyola, A. Methane emissions from anaerobic sludge digesters in Mexico: On-site determination vs. IPCC Tier 1 method. *Sci. Total Environ.* **2019**, *656*, 468–474. [CrossRef]
74. Vijay, V.; Subbarao, P.; Chandra, R. An evaluation on energy self–sufficiency model of a rural cluster through utilization of biomass residue resources: A case study in India. *Energy Clim. Chang.* **2021**, *2*, 100036. [CrossRef]
75. Ma, X.; Zhang, T.; Xie, Y.; Tan, Q. A simulation-assessment-optimization approach towards energy self-sufficiency and carbon reduction in regional-scale sewage systems. *Resour. Conserv. Recycl.* **2022**, *187*, 106595. [CrossRef]
76. Masłoń, A.; Czarnota, J.; Szczyrba, P.; Szaja, A.; Cieplak, S.J.; Łagód, G. Assessment of energy self-sufficiency of wastewater treatment plants—A case study from Poland. *Energies* **2024**, *17*, 1164. [CrossRef]
77. Dhara, S.; Das, P.P.; Uppaluri, R.; Purkait, K.M. *Biological Approach for Energy Self-Sufficiency of Municipal Wastewater Treatment Plants*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 235–260.
78. Feng, Y.; Rosa, L. Global biomethane and carbon dioxide removal potential through anaerobic digestion of waste biomass. *Environ. Res. Lett.* **2024**, *19*, 024024. [CrossRef]
79. Woo, T.; Charmchi, A.; Ifaei, P.; Heo, S.; Nam, K.; Yoo, C. Three energy self-sufficient networks of wastewater treatment plants developed by nonlinear bi-level optimization models in Jeju Island. *J. Clean. Prod.* **2022**, *379*, 134465. [CrossRef]
80. Li, H.H.; Zhang, T.; Tsang, D.C.W.; Li, G.X. Effects of external additives biochar, bentonite, phosphate, on co-composting for swine manure and corn straw. *Chemosphere* **2020**, *248*, 125927. [CrossRef]
81. Li, H.H.; Zhang, T.; Shaheen, S.M.; Abdelrahman, H.; Ali, E.F.; Bolan, N.S.; Li, G.X.; Rinklebe, J. Microbial inoculants and struvite improved organic matter humification and stabilized phosphorus during swine manure composting: Multivariate and multiscale investigations. *Bioresour. Technol.* **2022**, *351*, 126976. [CrossRef]
82. Zhang, T.; Wu, X.S.; Shaheen, S.M.; Abdelrahman, H.; Ali, E.F.; Bolan, N.S.; Li, G.X.; Tsang, D.C.W.; Rinklebe, J. Improving the humification and phosphorus flow during swine manure composting: A trial for enhancing the beneficial applications of hazardous biowastes. *J. Hazard. Mater.* **2022**, *425*, 127906. [CrossRef]
83. Zhang, T.; Li, H.H.; Yan, T.; Shaheen, S.M.; Niu, Y.Q.; Zhang, Y.Y.; Abdelrahman, H.; Ali, E.F.; Bolan, N.S.; Rinklebe, J. Organic matter stabilization and phosphorus activation during vegetable waste composting: Multivariate and multiscale investigation. *Sci. Total Environ.* **2023**, *891*, 164608. [CrossRef] [PubMed]
84. Rekleitis, G.; Haralambous, K.; Loizidou, M.; Aravossis, K. Utilization of agricultural and livestock waste in anaerobic digestion: Applying the biorefinery concept in a circular economy. *Energies* **2020**, *13*, 4428. [CrossRef]
85. Sebastian, P.; Kalaiselvi, K.; Suganya, K.; Muthusamy, S.; Poornima, R.; Bush, R. Novel resources recovery from anaerobic digestates: Current trends and future perspectives. *Crit. Rev. Environ. Sci. Technol.* **2021**, *52*, 1915–1999.
86. He, X.Y.; Zhang, T.; Niu, Y.; Xue, Q.; Ali, E.F.; Shaheen, S.M.; Tsang, D.C.W.; Rinklebe, J. Impact of catalytic hydrothermal treatment and Ca/Al-modified hydrochar on lability, sorption, and speciation of phosphorus in swine manure: Microscopic and spectroscopic investigations. *Environ. Pollut.* **2022**, *299*, 118877. [CrossRef] [PubMed]
87. Su, X.H.; Zhang, T.; Zhao, J.Y.; Mukherjee, S.; Alotaibi, N.M.; Elwafa, A.S.F.; Tran, H.T.; Bolan, N.S. Phosphorus fraction in hydrochar from co-hydrothermal carbonization of swine manure and rice straw: An optimization analysis based on response surface methodology. *Water* **2024**, *16*, 2208. [CrossRef]
88. Przydatek, G.; Wota, A. Analysis of the comprehensive management of sewage sludge in Poland. *J. Mater. Cycles Waste Manag.* **2019**, *22*, 80–88. [CrossRef]
89. Bora, R.; Richardson, R.; You, F. Resource recovery and waste-to-energy from wastewater sludge via thermochemical conversion technologies in support of circular economy: A comprehensive review. *BMC Chem. Eng.* **2020**, *2*, 8. [CrossRef]
90. Seruga, P. The municipal solid waste management system with anaerobic digestion. *Energies* **2021**, *14*, 2067. [CrossRef]
91. Tomić, T.; Kremer, I.; Schneider, D. Economic efficiency of resource recovery—Analysis of time—Dependent changes on sustainability perception of waste management scenarios. *Clean Technol. Environ. Policy* **2021**, *24*, 543–562. [CrossRef]

92. Đurđević, D.; Žiković, S.; Blecich, P. Sustainable sewage sludge management technologies selection based on techno-economic-environmental criteria: Case study of Croatia. *Energies* **2022**, *15*, 3941. [CrossRef]
93. Adenuga, O.; Mpofu, K.; Modise, K. An approach for enhancing optimal resource recovery from different classes of waste in South Africa: Selection of appropriate waste to energy technology. *Sustain. Futur.* **2020**, *2*, 100033. [CrossRef]
94. Dell'Orto, A.; Trois, C. Double-stage anaerobic digestion for biohydrogen production: A strategy for organic waste diversion and emission reduction in a South African municipality. *Sustainability* **2024**, *16*, 7200. [CrossRef]
95. Demirtas, U.M.; Dalke, R.; Pagilla, K. Sludge management and utilization for decarbonization. In *Pathways to Water Sector Decarbonization, Carbon Capture and Utilization*; IWA Publishing: London, UK, 2022; Volume 10, p. 171.
96. Hernández, J.S. Energy, environmental, resource recovery, and economic dimensions of municipal solid waste management paths in Mexico city. *Waste Manag.* **2021**, *136*, 321–336. [CrossRef] [PubMed]
97. Silva, A.; Brasil, Y.; Koch, K.; Amaral, M. Resource recovery from sugarcane vinasse by anaerobic digestion–a review. *J. Environ. Manag.* **2021**, *295*, 113137. [CrossRef]
98. Zarei, M. Wastewater resources management for energy recovery from circular economy perspective. *Water-Energy Nexus* **2020**, *3*, 170–185. [CrossRef]
99. Jin, C.; Sun, S.; Yang, D.; Sheng, W.; Ma, Y.; He, W.; Li, G. Anaerobic digestion: An alternative resource treatment option for food waste in China. *Sci. Total Environ.* **2021**, *779*, 146397. [CrossRef]
100. Choudhury, A.; Lepine, C.; Witarsa, F.; Good, C. Anaerobic digestion challenges and resource recovery opportunities from land-based aquaculture waste and seafood processing byproducts: A review. *Bioresour. Technol.* **2022**, *354*, 127144. [CrossRef] [PubMed]
101. Shah, H.H.; Amin, M.; Pepe, F. Maximizing resource efficiency: Opportunities for energy recovery from municipal solid waste in Europe. *J. Mater. Cycles Waste Manag.* **2023**, *25*, 2766–2782. [CrossRef]
102. Amodeo, C.; Hattou, S.; Buffiere, P.; Benbelkacem, H. Temperature phased anaerobic digestion (TPAD) of organic fraction of municipal solid waste (OFMSW) and digested sludge (DS): Effect of different hydrolysis conditions. *Waste Manage.* **2021**, *126*, 21–29. [CrossRef] [PubMed]
103. Postawa, K.; Szczygieł, J.; Kułażyński, M. Innovations in anaerobic digestion: A model-based study. *Biotechnol. Biofuels* **2021**, *14*, 19. [CrossRef]
104. Archana, K.; Visckram, A.; Kumar, P.; Manikandan, S.; Saravanan, A.; Natrayan, L. A review on recent technological breakthroughs in anaerobic digestion of organic biowaste for biogas generation: Challenges towards sustainable development goals. *Fuel* **2024**, *358*, 130298. [CrossRef]
105. Loh, M.C.; Lues, R. Anaerobic digestion of lignocellulosic biomass: Substrate characteristics (challenge) and innovation. *Fermentation* **2023**, *9*, 755. [CrossRef]
106. Naquash, A.; Qyyum, M.; Haider, J.; Bokhari, A.; Lim, H.; Lee, M. State-of-the-art assessment of cryogenic technologies for biogas upgrading: Energy, economic, and environmental perspectives. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111826. [CrossRef]
107. Sevillano, C.A.; Pesantes, A.A.; Carpio, E.P.; Martínez, E.J.; Gómez, X. Anaerobic digestion for producing renewable energy—The evolution of this technology in a new uncertain scenario. *Entropy* **2021**, *23*, 145. [CrossRef] [PubMed]
108. Zhang, T.; Pasha, A.M.K.; Sajadi, S.M.; Jasim, D.J.; Esfahani, N.N.; Maleki, H.; Salahshour, S.; Baghaei, S. Optimization of thermophysical properties of nanofluids using a hybrid procedure based on machine learning, multi-objective optimization, and multi-criteria decision-making. *Chem. Eng. J.* **2024**, *485*, 150059. [CrossRef]
109. Cinar, S.; Cinar, S.O.; Wieczorek, N.; Sohoo, I.; Kuchta, K. Integration of artificial intelligence into biogas plant operation. *Processes* **2021**, *9*, 85. [CrossRef]
110. Yildirim, O.; Ozkaya, B. Prediction of biogas production of industrial scale anaerobic digestion plant by machine learning algorithms. *Chemosphere* **2023**, *335*, 138976. [CrossRef]
111. Swami, S.; Suthar, S.; Singh, R.; Kumar, A.T.; Gupta, L.; Sikarwar, S.V. Integration of anaerobic digestion with artificial intelligence to optimise biogas plant operation. In *Environment, Development and Sustainability*; Springer: New Delhi, India, 2023; pp. 1–31.
112. Cheah, C.G.; Chia, W.Y.; Lai, S.F.; Chew, K.W.; Chia, S.R.; Show, P.L. Innovation designs of industry 4.0 based solid waste management: Machinery and digital circular economy. *Environ. Res.* **2022**, *213*, 113619. [CrossRef] [PubMed]
113. Sheik, G.A.; Krishna, S.; Patnaik, R.; Ambati, R.S.; Bux, F.; Kumari, S. Digitalization of phosphorous removal process in biological wastewater treatment systems: Challenges, and way forward. *Environ. Res.* **2024**, *252*, 119133. [CrossRef]
114. Brémond, U.; Bertrandias, A.; Steyer, J.P.; Bernet, N.; Carrere, H. A vision of European biogas sector development towards 2030: Trends and challenges. *J. Clean. Prod.* **2021**, *287*, 125065. [CrossRef]
115. Lybæk, R.; Christensen, T.B.; Thomsen, T.P. Enhancing policies for deployment of industrial symbiosis—What are the obstacles, drivers and future way forward? *J. Clean. Prod.* **2021**, *280*, 124351. [CrossRef]
116. Nevzorova, T.; Karakaya, E. Explaining the drivers of technological innovation systems: The case of biogas technologies in mature markets. *J. Clean. Prod.* **2020**, *259*, 120819. [CrossRef]
117. Gustafsson, M.; Anderberg, S. Great expectations—Future scenarios for production and use of biogas and digestate in Sweden. *Biofuels* **2022**, *14*, 93–107. [CrossRef]
118. Magnusson, T.; Zanatta, H.; Larsson, M.; Kanda, W.; Hjelm, O. Circular economy, varieties of capitalism and technology diffusion: Anaerobic digestion in Sweden and Paraná. *J. Clean. Prod.* **2022**, *335*, 130300. [CrossRef]

119. Miszczuk, C.J.; Martinát, S.; Horst, V.D.D. Changes in feedstocks of rural anaerobic digestion plants: External drivers towards a circular bioeconomy. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111344. [CrossRef]
120. Martinát, S.; Chodkowska-Miszczuk, J.; Kulla, M.; Navrátil, J.; Klusáček, P.; Dvořák, P.; Novotný, L.; Krejčí, T.; Pregi, L.; Trojan, J.; et al. Best practice forever? Dynamics behind the perception of farm-fed anaerobic digestion plants in rural peripheries. *Energies* **2022**, *15*, 2533. [CrossRef]
121. Song, J.; Wang, Y.; Zhang, S.; Song, Y.; Xue, S.; Liu, L.; Lvy, X.; Wang, X.; Yang, G. Coupling biochar with anaerobic digestion in a circular economy perspective: A promising way to promote sustainable energy, environment and agriculture development in China. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110973. [CrossRef]
122. Rizzioli, F.; Bertasini, D.; Bolzonella, D.; Frison, N.; Battista, F. A critical review on the techno-economic feasibility of nutrients recovery from anaerobic digestate in the agricultural sector. *Sep. Purif. Technol.* **2023**, *306*, 122690. [CrossRef]
123. Jacob, S.; Upadrasta, L.; Banerjee, R. Bottlenecks in biomethane production from agro-industrial wastes through anaerobic digestion. In *Practices and Perspectives in Sustainable Bioenergy*; Green Energy and Technology; Springer: New Delhi, India, 2020; pp. 75–104.
124. Deng, Y.X.; Zhang, T.; Clark, J.; Aminabhavi, T.; Kruse, A.; Tsang, D.C.W.; Sharma, B.K.; Zhang, F.S.; Ren, H.Q. Mechanisms and modelling of phosphorus solid-liquid transformation during the hydrothermal processing of swine manure. *Green Chem.* **2020**, *22*, 5628–5638. [CrossRef]
125. Shanmugam, S.; Mathimani, T.; Rene, R.E.; Geo, E.V.; Arun, A.; Brindhadevi, K.; Pugazhendhi, A. Biohythane production from organic waste: Recent advancements, technical bottlenecks and prospects. *Int. J. Hydrogen Energy* **2021**, *46*, 11201–11216. [CrossRef]
126. Wang, Y.; Zhang, T.; Westerhoff, P.; Jiang, R.F.; Ren, H.Q.; Yang, Y.; Li, Z. Microwave-assisted digestion and NaOH treatment of waste-activated sludge to recover phosphorus by crystallizing struvite. *Environ. Technol.* **2017**, *38*, 1211–1222. [CrossRef] [PubMed]
127. Xie, S.Y.; He, X.Y.; Alshehri, A.M.; Elwafa, A.S.F.; Zhang, T. Elevated effect of hydrothermal treatment on phosphorus transition between solid-liquid phase in swine manure. *Results Eng.* **2024**, *24*, 102887. [CrossRef]
128. Hoo, P.; Hashim, H.; Ho, W. Towards circular economy: Economic feasibility of waste to biomethane injection through proposed feed-in tariff. *J. Clean. Prod.* **2020**, *270*, 122160. [CrossRef]
129. Zieliński, M.; Kazimierowicz, J.; Dębowski, M. Advantages and limitations of anaerobic wastewater treatment—Technological basics, development directions, and technological innovations. *Energies* **2022**, *16*, 83. [CrossRef]
130. Mosquera, A.L.; Alvarado, A.A.; Arrieta, R.M.; Cattaneo, C.; Rene, E.; Depraect, G.O. Production of solid biofuels from organic waste in developing countries: A review from sustainability and economic feasibility perspectives. *Sci. Total Environ.* **2021**, *795*, 148816. [CrossRef] [PubMed]
131. Vinardell, S.; Astals, S.; Koch, K.; Alvarez, M.J.; Dosta, J. Co-digestion of sewage sludge and food waste in a wastewater treatment plant based on mainstream anaerobic membrane bioreactor technology: A techno-economic evaluation. *Bioresour. Technol.* **2021**, *330*, 124978. [CrossRef]
132. Kehrein, P.; Loosdrecht, V.M.; Osseweijer, P.; Garfí, M.; Dewulf, J.; Posada, J. A critical review of resource recovery from municipal wastewater treatment plants—Market supply potentials, technologies and bottlenecks. *Environ. Sci. Water Res. Technol.* **2020**, *6*, 877–910. [CrossRef]
133. Mateescu, C.; Dima, A.D. Critical analysis of key barriers and challenges to the growth of the biogas sector: A case study for Romania. *Biomass Convers. Biorefin.* **2020**, *12*, 5989–6002. [CrossRef]
134. Abanades, S.; Abbaspour, H.; Ahmadi, A.; Das, B.; Ehyaei, M.; Esmaeilion, F.; Assad, M.; Hajilounezhad, T.; Jamali, D.; Hmida, A.; et al. A critical review of biogas production and usage with legislations framework across the globe. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 3377–3400. [CrossRef]
135. Ackrill, R.; Abdo, H. On-farm anaerobic digestion uptake barriers and required incentives: A case study of the UK East Midlands region. *J. Clean. Prod.* **2020**, *264*, 121727. [CrossRef]
136. Ahmed, N.; Qamar, S.; Jabeen, G.; Yan, Q.; Ahmad, M. Systematic analysis of factors affecting biogas technology acceptance: Insights from the diffusion of innovation. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102122. [CrossRef]
137. O'Connor, S.; Ehimen, E.; Pillai, S.; Power, N.; Lyons, G.; Bartlett, J. An investigation of the potential adoption of anaerobic digestion for energy production in Irish farms. *Environments* **2021**, *8*, 8. [CrossRef]
138. Mancini, E.; Raggi, A. Out of sight, out of mind? The importance of local context and trust in understanding the social acceptance of biogas projects: A global scale review. *Energy Res. Soc. Sci.* **2022**, *91*, 102697. [CrossRef]
139. Duquennoi, C.; Martinez, J. European Union's policymaking on sustainable waste management and circularity in agroecosystems: The potential for innovative interactions between science and decision-making. *Front. Sustain. Food Syst.* **2022**, *6*, 937802. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.