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REVIEW ARTICLE

Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: a review

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Abstract

Anaerobic digestion constitutes a sustainable method for waste management and renewable energy generation, addressing significant environmental and societal challenges. The growing global waste crisis and the increasing momentum toward sustainable energy solutions emphasize the critical need to enhance anaerobic digestion technology for improved efficiency and environmental advantages. This process mitigates waste accumulation, enhances energy security, and reduces greenhouse gas emissions, providing a feasible solution within the framework of a circular bioeconomy. Here, we review the principles of anaerobic digestion and biogas production, focusing on agricultural waste and the utilization of biogas for energy within a sustainable framework. We specifically explore biogas applications in rural and industrial settings, assess the environmental impacts, and discuss the regulatory landscape with insights from China and Europe. This study reveals that the strategic implementation of anaerobic digestion can markedly improve energy yield and sustainability, demonstrating how focused policies and advanced technological practices can optimize biogas utilization. The review enhances comprehension of environmental impacts, emphasizing insights from China and Europe as key examples.

Keywords Anaerobic digestion · Biogas · Biomass · Agricultural waste · Bioenergy · Circular economy

Introduction

The global increase in waste generation, especially organic waste from agricultural practices, presents considerable environmental challenges, including land utilization problems, pollution, and the intensification of climate change. Simultaneously, the decomposition of organic waste in landfills produces methane [13]. Consequently, sustainable management of this waste is essential. Furthermore, traditional energy sources, primarily fossil fuels, significantly contribute to global greenhouse gas emissions, resulting in climate change and environmental deterioration [122]. Consequently, diminishing dependence on these energy sources by transitioning to renewable alternatives such as biogas can alleviate these impacts [7]. Therefore, by implementing advancing technologies, such as anaerobic digestion, societies can transform waste into energy, improving self-sufficiency and mitigating vulnerability to global energy price fluctuations [133]. This transition not only ensures energy availability but also strengthens local economies by creating employment opportunities in novel and developing sectors. Furthermore, inadequate waste management can result in significant health hazards, such

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as respiratory disorders from incinerating waste, waterborne diseases due to contamination, and various public health emergencies [42]. Consequently, effective waste-to-energy methods can mitigate these health concerns while decreasing waste volume [126].

In rural regions, where access to national power grids may be restricted, biogas is a dependable energy source. This accessibility can markedly enhance the quality of life, alleviating energy poverty and boosting local economic endeavors [21]. Anaerobic digestion facilitates a circular economy by repurposing waste materials as resources, thereby reducing waste and enhancing resource efficiency [8]. This method diminishes environmental impact while promoting economic stability by generating value from waste. Aside from biogas production, anaerobic digestion generates a nutrient-rich digestate and may serve as an organic fertilizer, improving soil fertility and decreasing reliance on synthetic fertilizers [9]. The management, processing, and application of digestate pose challenges, especially concerning nutrient regulation, storage, transportation, and adherence to regulations for its use as fertilizer [172]. Integrating biogas production into current agricultural and energy systems efficiently, without causing disruption, presents design and operational challenges. This encompasses integrating anaerobic digestion with other renewable energy technologies or current waste management systems [122].

Moreover, the global electrical sector primarily depends on natural gas; however, renewable alternatives such as biogas derived from waste biomass could serve as adequate replacements, providing solutions for power and heat generation [130]. Biogas derived from waste biomass is a feasible renewable energy option that can replace natural gas and produce heat and electricity. Biogas has the potential to be converted into biomethane via upgrading or used for combined heat and power generation through combustion [7], making biogas a promising and sustainable approach. Biogas upgrading to produce biomethane can achieve a high-energy conversion efficiency, resulting in biomethane with a purity of more than 95–97% [2]. Several current biogas plants have natural gas storage facilities that can be used for biomethane without any modifications [133]. Nevertheless, biomethane is only capable of substituting natural gas and no other energy source. The integrated cogeneration system can provide electricity and heat to the national power grid while producing low-pressure steam from the waste gases [1]. However, conducting a comprehensive environmental impact assessment is crucial even though biogas provides a more environmentally friendly option than conventional energy sources. The evaluation should include a comprehensive analysis of the whole life cycle of biogas production and utilization, spanning from raw materials to their final use, to determine the overall environmental impact [11].

This review integrates insights into microbiology, engineering, economics, environmental considerations, and policy impacts, offering a comprehensive perspective on anaerobic digestion. This interdisciplinary approach is essential for comprehending the intricate interactions within biogas systems and formulating effective interventions. Furthermore, numerous reviews address biogas production from diverse organic waste materials. This review emphasizes the utilization of agricultural waste, and the substantial and frequently underexploited resources, providing comprehensive analysis and examples of how this sector can be enhanced for improved energy production and environmental results. Moreover, this review offers a global perspective on policy developments and implementation challenges in biogas adoption, specifically examining China and Europe, despite many reviews concentrating on regional data. This review extends conventional discourse on greenhouse gas emissions and energy efficiency, encompassing a comprehensive assessment of environmental impacts, including the life cycle analysis of biogas systems and the effects of digestate as a biofertilizer on soil health. The review presents a prospective outlook, addressing future research requirements, possible technological advancements, and strategic suggestions for policymakers and practitioners in the field.

Here, we point out, for the first time, the anaerobic digestion process, emphasizing the conversion of agricultural waste into biogas, a renewable energy source that plays a crucial role in waste management, energy security, and environmental sustainability. The review also examines the technological, environmental, and regulatory aspects of biogas production, highlighting biogas applications in rural and industrial contexts and the policy frameworks of biogas and digestate influencing biogas industry development in areas, such as China and Europe. The main structure of this article is shown in Fig. 1, highlighting the main route of biogas production and possible approaches to biogas utilization aligned with the main goals of the current study.

Conventional versus sustainable energy sources

Conventional and sustainable energy sources compete in the dynamic global energy production scene. Coal and petroleum, which capture energy from old organic material, were secured in manufacturing eras [36]. However, due to their environmental impact and finite nature, there has been a shift toward sustainable alternatives [99]. Solar, wind, and biomass are sustainable energy sources that use the planet's natural and renewable processes without depleting finite supplies or degrading the environment [126]. This highlights a shift toward greener and more robust energy production technologies, demonstrating a commitment to a sustainable

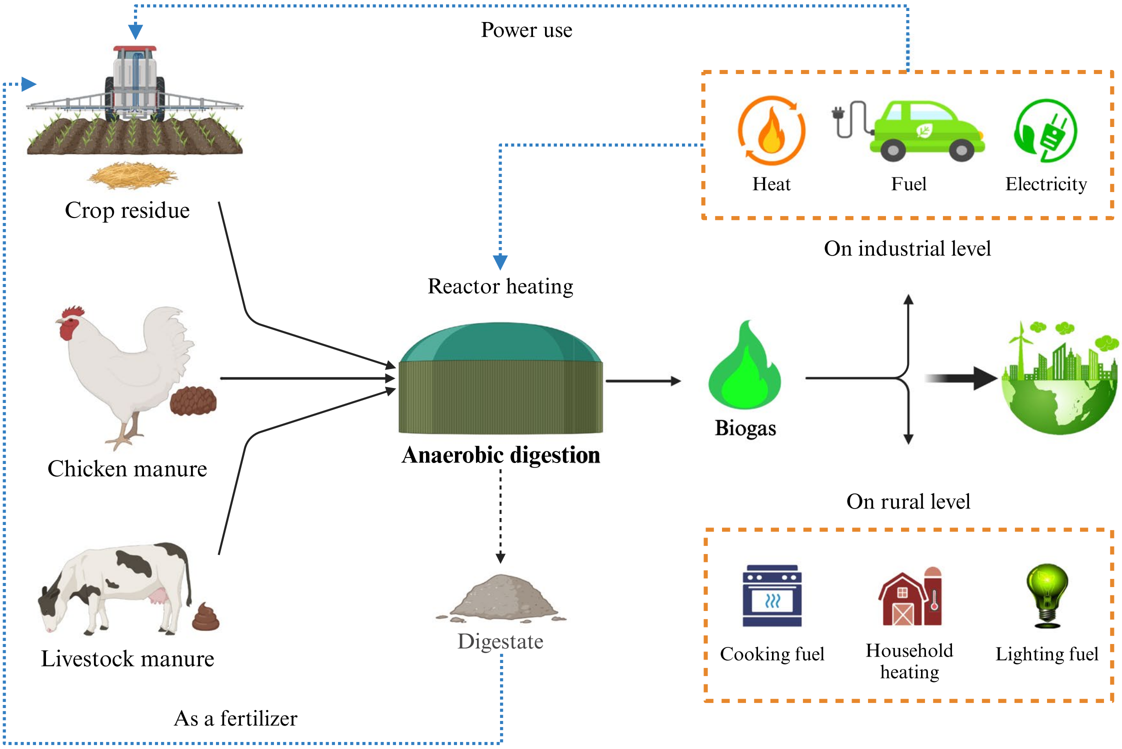

Fig. 1 Typical process flow for biogas production from agricultural waste and crude biogas utilization within the circular economy framework. Biogas production from agricultural waste has a high potential for producing renewable energy by using crude biogas to produce different types of energy, such as heat, electricity, and fuel, on both rural and industrial scales

future. Sustainable energy offers a lifestyle that aligns more with the Earth's ecological processes, especially as the world addresses climate change and the depletion of fossil fuel reserves [172].

Conventional energy

Conventional sources of energy have been widely used to meet energy requirements. However, due to their far higher consumption rate than their synthesis rate, these energy sources have been depleted and are not replenished [6]. Moreover, conventional forms of energy, such as coal, gas, and oil, emit harmful pollutants that not only damage the environment but also have negative impacts on human health [148]. Conventional energy sources can cause several forms of pollution, such as air pollution, acid rain, and greenhouse gases. Burning fossil fuels emits chemicals and particles into the atmosphere, including carbon dioxide, carbon monoxide, nitrogen oxide, hydrocarbons, and sulfur dioxide [89].

Petroleum, also known as crude oil, is a crucial component of the global energy sector, providing fuel for transportation, industry, and other applications [6]. According to Ritchie et al. [144], global oil consumption for primary energy production in 2022 exceeded 52,970 terawatts, which is the largest conventional energy source out of 178,900 terawatts. Although oil has a high-energy density and a well-established infrastructure for extraction, refining, and distribution, certain activities, such as oil spills, particularly during extraction and transportation, are becoming increasingly worrisome from an environmental standpoint [139]. The increasing focus on biofuels and electric vehicles has the potential to redefine the significance of petroleum.

As a conventional energy source, coal has always been a fundamental component of worldwide energy generation. Globally, coal contributes 44,854 terawatts of primary energy out of the total energy consumed worldwide, ranking second after oil [144]. Coal is a hydrocarbon fuel derived from the organic matter of ancient plants that perished millions of years ago and is found in extensive global deposits [168]. Coal is a widely available energy source with a well-developed infrastructure for mining and consumption. However, there are some significant drawbacks, such as high carbon content leading to substantial greenhouse gas emissions [125]. Furthermore, significant environmental deterioration is caused by mining activities. Still, carbon capture and storage technologies can potentially improve the environmental impact of coal [105].

Additionally, electricity is a versatile form of energy that powers residences, industries, and technological breakthroughs. Coal is the primary source of electricity production globally, accounting for about 36%, followed closely by gas at 22% [144]. Although not a primary energy source, energy can be derived from various sources, including fossil fuels, renewable energy, and nuclear power. However, relying on fossil fuels for electricity generation results in a substantial release of emissions [174]. The ongoing transition toward renewable energy sources is driven by environmental concerns and technological progress. Also, the dependability of renewable energy is being improved by advancements in energy storage technology [101, 126].

For years, conventional energy sources, such as fossil fuels, have been the primary energy source. However, burning fossil fuels has significant environmental impacts that affect both the natural world and human health [125]. The most common environmental problems caused by burning fossil fuels include climate change, air pollution, water pollution, land use, and waste production [24, 151]. In 2019, the International Energy Agency reported that worldwide carbon dioxide emissions from energy sources hit an unprecedented level of 33 gigatons. The electricity industry was the primary source of emissions, responsible for about 42% of the total carbon dioxide emissions connected to energy [65]. Regarding fuel types, coal was the largest emitter, accounting for 42% of energy-related carbon dioxide emissions, followed by oil at 34% and natural gas at 20% [66]. In addition, the International Energy Agency has calculated that in order to achieve the goal of limiting global warming to 1.5 °C, as outlined in the Paris Agreement, carbon dioxide emissions from the energy sector must decrease by 45% by 2030 compared to 2010 levels, and ultimately reach a state of net-zero emissions by 2050 [23, 59].

The unequivocal message is being conveyed worldwide as the impacts of climate change are intensifying, and greenhouse gas emissions must be reduced [167]. The 2020 global greenhouse gas emissions were mostly caused by the top seven polluters, which are China, the EU27, India, Indonesia, Brazil, the Russian Federation, and the USA. International transport also significantly accounted for 55% of the total global greenhouse gas emissions [165]. According to Our World in Data, the energy sector (i.e., heat, electricity, and transport) represents about 73%, the agricultural sector, including forestry and land use, denotes 18%, and the industrial processes account for 5%. In comparison, the waste sector contributes 3% [145]. This analysis shows that various industries and procedures contribute to global emissions. Therefore, addressing climate change is not a simple task [126]. To achieve net-zero emissions, progress must be made across multiple sectors. Therefore, due to the necessity of reducing greenhouse gas emissions to combat climate change, bioenergy has emerged as a possible solution [143].

Bioenergy

Given the need to decrease greenhouse gas emissions in order to address climate change, bioenergy has emerged as a viable remedy [143]. Bioenergy can efficiently mitigate greenhouse gas emissions [108, 172]. The use of organic matter for energy production releases carbon dioxide into the atmosphere, which was initially stored in the organic matter [117]. However, the renewable nature of the organic matter used for bioenergy allows for the carbon emissions produced during combustion to be sequestered through subsequent growth [83].

Biogas, an environmentally friendly energy source produced by breaking down organic waste without the presence of oxygen, may be used as a replacement for natural gas in heating and cooking [12, 50]. The aforementioned approach reduces the emission of greenhouse gases caused by non-renewable energy sources and provides a practical solution for waste management [92]. Biofuels, such as ethanol and biodiesel, can be produced from organic matter, including crops, and are a feasible energy source for transportation [108]. Implementing such a strategy can reduce transportation emissions while creating a new market for farmers and rural communities [22].

The viability of bioenergy depends on the specific biomass used, the cultivation and harvesting methods employed, and the energy conversion mechanisms implemented for energy generation [33, 107]. The cultivation of bioenergy crops on arable land may worsen deforestation and food insecurity. Therefore, the use of sustainable methods ensures that bioenergy is produced with a responsible and ethical approach [107].

In this context, the net-zero emissions track involves significant reforms in the global energy structure since low-emission sources can significantly increase and replace the unabated sources throughout the entire energy sector. According to the International Energy Agency, there was a notable increase of approximately 125 exajoules in low-emissions sources of supply from 2021 to 2030. As energy access objectives are achieved, the use of biomass is gradually being phased out. Moreover, modern bioenergy and solar are expected to experience the most significant increase up to 2030, with approximately 35 and 28 exajoules, respectively [67]. Furthermore, the trend toward sustainable alternatives is gaining momentum due to concerns about affordability and security brought on by the global energy crisis. This has resulted in a substantial increase in investment in clean energy technologies, surpassing spending on fossil fuels. According to the International Energy Agency's World Energy Investment 2023 report, investment in clean energy is expected to increase by 24% annually from 2021 to 2023, driven primarily by renewable energy and electric vehicles. In contrast, investment in fossil fuels is expected to increase by only 15% during the same period [68].

Environmental credits, such as carbon credits or offsets, are crucial worldwide in addressing climate change. When comparing bioenergy to conventional energy, bioenergy systems acquire these credits because they are inherently carbon–neutral [18]. Commitments to carbon neutrality are evidence of leadership in responding to the climate problem. As of March 2024, approximately 150 national governments and the European Union have pledged to achieve net carbon neutrality by 2050, with some aiming for 2030 or 2070. Among these countries, 27 are in the in-law phase, 51 are in the policy document phase, 9 are in the declaration phase, and 57 are in the proposed phase [40]. Bioenergy, like other energy sources, emits carbon dioxide upon combustion. Nevertheless, plants absorb carbon throughout their development, making bioenergy systems environmentally neutral regarding carbon emissions [128]. The absorption and release of carbon is an integral part of the natural carbon cycle. Additionally, bioenergy systems emit significantly less than non-renewable ones [9]. Bioenergy projects may be eligible for carbon offsets, especially when they significantly reduce greenhouse gas emissions compared to typical scenarios. An example project that can provide carbon offsets involves collecting methane emissions from organic waste [83, 143].

In this regard, anaerobic digestion of organic waste, such as agricultural waste or other forms of biomass, not only generates bioenergy in the form of biogas but also reduces methane emissions, which are a potent greenhouse gas [132]. Such projects that capture and use methane can provide carbon offsets [18]. Practically, Alengebawy et al. [9] investigated the environmental impacts of using rice straw as an agricultural source of biomass to generate bioenergy via three sustainable approaches, including anaerobic digestion, gasification, and briquetting. They compared these three projects with rice straw open field burning on a large scale and found that all bioenergy scenarios significantly reduced emissions compared to the reference scenario. Bioenergy systems are a leading source of environmental credits due to their renewability and significant reduction of greenhouse gas emissions. These systems actively contribute to carbon offset markets and provide information on how to recognize and endorse these positive environmental effects [107]. To sum up, Fig. 2

Fig. 2 Forms and characteristics of conventional and sustainable/bioenergy energy. While conventional energy forms include coal, oil, and natural gas, common sustainable energy forms are biogas, bioheat, and bioelectricity. Sustainable forms of energy have several advantages compared to conventional ones, such as waste reduction, clean energy generation, and sustainable supply

provides a comparison between conventional energy and bioenergy in terms of their types and characteristics.

Statistics on conventional and sustainable energy in China and Europe

According to the Environmental Energy Agency, world demand for coal, the most prominent conventional energy source, has increased by 1.4% in 2023, reaching a record 8.5 billion tons. However, there are significant regional differences, with most developed countries expected to decrease their consumption in 2023. The European Union and the US are projected to experience significant losses of roughly 20% each, setting new records. Currently, India and China, two of the world's fastest-growing nations, are experiencing a surge in demand for electricity. This demand is primarily driven by rising electricity consumption and insufficient hydropower output [69]. However, renewable energy has made significant progress, and 2022 was a record year for renewable power capacity additions at 340 gigawatts. The implementation of significant legislation in 2022, such as REPowerEU in the European Union and China's 14th five-year plan for renewable energy, is expected to contribute to the rapid expansion of renewable power in the coming years. Currently, contemporary bioenergy is the most significant contributor to renewable energy globally, accounting for 55% of all renewable energy sources and making a substantial 6% contribution to the overall global energy supply. In March 2023, the council and parliament reached a preliminary agreement on adjusting the renewable energy directive. The agreement implements the cascading approach to improve the sustainability of biomass energy while recognizing national interests. By 2030, the European Union aims to increase biomethane output to 35 billion cubic meters, a significant increase from the 3.5 billion cubic meters produced in 2022. In September 2022, the Biomethane Industrial Partnership was formed to help achieve this goal [70].

In China, total energy consumption in 2022 reached 159.4 exajoules, accounting for approximately 26.4% of global consumption, a significantly higher percentage than Europe's 79.8 exajoules and other countries, as shown in Table 1. Non-renewable energy sources accounted for about 146 exajoules in China, compared to 68.8 exajoules in Europe, out of a global total of 559 exajoules. On the other hand, non-renewable energy sources still dominate the energy sector, with renewable energy sources contributing only 13.3 exajoules in China and 11.6 exajoules in Europe [71, 72], Energy [43]. Nations must adopt a renewable energy approach to transition to sustainability. According to statistics from Our World in Data, greenhouse gas emissions from the energy sector reached 54.6 billion tons worldwide in 2021. China has the highest carbon emissions at 13.7 billion tons, while Europe contributed 6.8 billion tons in 2023 [129], reflecting the extent to which the climate is affected by the energy sector in the entire world.

In summary, conventional and sustainable energy sources have divergent effects on the environment and distinct functions in reducing emissions. Traditional energy sources have detrimental impacts on ecosystems and contribute to climate change. On the other hand, bioenergy, which is a sustainable option, can decrease emissions and promote environmental advantages. The environmental credits associated with bioenergy demonstrate how the use may contribute to a cleaner and more sustainable energy environment. Figures on energy consumption trends in China and Europe provide valuable information on the present status of both conventional and sustainable energy use. These figures emphasize the urgent need to shift toward more ecologically friendly energy sources.

Biogas from agricultural waste for sustainable energy

The global emphasis on biogas production from agricultural waste has significantly increased due to the growing need for clean energy and effective waste management solutions [17]. The biogas industry is a swiftly expanding sector,

Table 1 A comparison of conventional and sustainable energy systems in China and Europe, with a reference to the worldwide data

Category	World	China	Europe	References
Total energy consumption 2022 (exajoules)	604	159.4	79.8	[43]
Total energy supply 2022 (exajoules)	632	159.7	78	[73]
Net energy imports 2021 (petajoules)	Not available	37,352	33,912	[71, 72]
Share of non-renewables 2022 (exajoules)	558.9	146	69.8	[43]
Share of renewables 2022 (exajoules)	45.2	13.3	11.6	[43]
Greenhouse gas emission 2021 (billion tons)	54.6	13.7	6.8	[129]
Carbon dioxide emission 2022 (billion tons)	37	11.4	5	[129]

China has the highest values in terms of different categories, which is mostly due to the higher population compared to Europe. According to global statistics, China and Europe have the highest portion of the world's population assuming an increasingly significant role in shifting toward a more sustainable energy system [106]. Farming activities produce significant waste, including agricultural leftovers, animal manures, and other organic by-products [27, 97]. Historically, these wastes have been regarded as environmental contaminants if not appropriately handled. Nevertheless, with the progress in biogas technology, the possibility to convert these agricultural wastes into significant energy-generating resources is now high. This conversion method not only reduces the environmental effect of waste but also helps the circular economy by recycling nutrients back into the soil [106]. Biogas is produced by the anaerobic digestion of organic materials, such as agricultural waste, animal manure, food waste, and sewage sludge. This process is achieved by introducing organic matter into a digester, which undergoes anaerobic bacteria degradation [120]. The principal constituents of biogas, methane, and carbon dioxide are generated throughout this procedure. Subsequently, the unprocessed biogas can undergo a purification process, compression, and combustion and be used as a source of energy for power production, heating, or transportation purposes [17, 107]. Biogas production steps and related processes are shown in Fig. 3.

A notable benefit of biogas is that it is a sustainable energy source derived from diverse organic waste streams. The utilization of waste not only decreases waste and greenhouse gas emissions but also offers a significant energy resource [106]. The production of biogas can yield supplementary advantages, including the mitigation of odors emanating from manure [80], enhancement of soil fertility via the generation of biofertilizers [5], and the establishment of novel economic prospects for rural societies [110]. In addition, the generation of biogas effectively mitigates greenhouse gas emissions by trapping methane that would otherwise be sent into the atmosphere through the decomposition of organic waste [91]. Methane is a very effective greenhouse gas, with a global warming potential 25 times higher than carbon dioxide over 100 years. The biogas sector has experienced a substantial expansion recently, primarily due to policy incentives, technological progress, and a rising need for sustainable energy sources [106]. Various technologies have been developed by the industry to enhance the efficacy of biogas production and optimize the utility of biogas as a fuel source, as reported by Aryal et al. [16]. For instance, co-digestion involves the incorporation of several waste streams in a solitary digester. According to Qian et al. [138], this method has been shown to enhance biogas production and optimize the financial viability of biogas initiatives.

The biogas industry encounters several obstacles, such as significant initial expenditures, intricate regulatory structures, and the requirement for superior feedstocks [64]. The potential of the industry to tackle these challenges has been evidenced by using innovative financing mechanisms, enhanced technology, and stakeholder collaboration [54]. According to Atelge et al. [17], the biogas sector presents a viable remedy for tackling energy and environmental predicaments. Biogas produces renewable energy to mitigate greenhouse gas emissions, offers alternatives to waste management, and fosters rural development. The growing and developing sector can play an increasingly important role in assisting the transition toward a more sustainable energy system [124].

Biogas industry in China and Europe

The biogas sector has been experiencing notable progress in China and Europe as both areas endeavor to achieve their renewable energy objectives and mitigate greenhouse gas emissions [115]. The biogas industries in the regions above exhibit certain commonalities, yet they also present notable

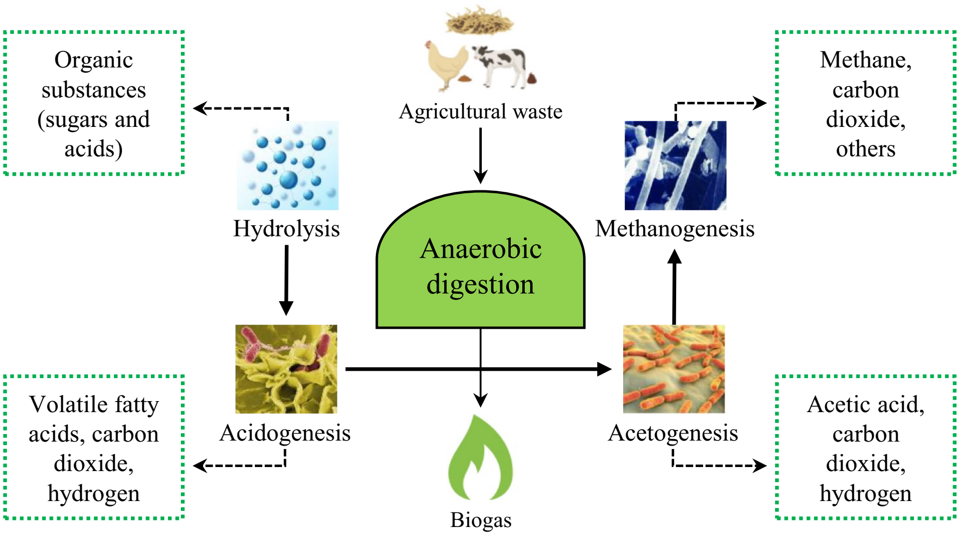

Fig. 3 Overview of biogas production and the processes of anaerobic digestion. The anaerobic digestion process for biogas generation usually occurs within a sealed reactor designed to maintain anaerobic conditions. The process consists of four primary stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Agricultural waste's organic matter can be transformed into biogas, with the remaining portion referred to as digestate

distinctions concerning their evolution, regulations, and obstacles [153]. The development of the biogas sector in China has been motivated by the imperative to tackle the issues associated with managing agricultural waste, alongside the state's pledge to mitigate the impact of greenhouse gas emissions [171]. The predominant utilization of biogas in China is for electricity generation and heating, while a minor fraction is allocated for transportation [170]. The Chinese government has enacted a range of laws and incentives to promote the development of the biogas industry. These measures include financial support for biogas initiatives, feed-in tariffs for biogas-generated electricity, and tax exemptions for biogas equipment [86]. The government has also implemented regulations to enhance the potential of biogas production and guarantee the sustainable and responsible development of biogas projects [124].

According to China's profile of statistics reported by the International Energy Agency in 2020, biofuels accounted for 5.6 million terajoules of Chinese energy supply, representing 3.8% of the total energy supply, while the highest portion was recorded for coal (89 million terajoules), followed by oil (27.7 million terajoules). This high portion of non-renewable sources raises the alarm for considering more renewable energy sources to achieve sustainability [74]. According to the National Bureau of Statistics of China, the number of biogas plants in 2019 reached 40 million household biogas plants, 118,000 small- and medium-sized biogas plants, and about 8720 large-scale biogas plants. The annual output of biogas in the country was about 19 billion cubic meters, of which about 16 billion cubic meters were from household and small-scale plants, while about 3 billion cubic meters were from medium- and large-scale plants [118]. Biogas projects in China are primarily driven by agricultural and rural development policies to promote renewable energy and improve energy access in rural areas. Biogas plants also contribute to sustainable agriculture by producing biofertilizers, which amounted to 1.05 million tons in 2019 [118].

Moreover, the Chinese government has released the 14th five-year plan (2021–2025) to develop modern energy systems. According to reports of the National Energy Administration of China, the Chinese government has set a target to increase the annual domestic energy production capacity to more than 4.6 billion tons of standard coal by 2025. Assumptions report that the yearly production of crude oil will experience a resurgence and attain a state of equilibrium at 200 million tons, while the yearly production of natural gas is anticipated to exceed 230 billion cubic meters by 2025. The Chinese government has also set a target to incrementally enhance the percentage of non-fossil fuel energy utilization to approximately 20% by 2025. Additionally, the proportion of non-fossil fuel energy production is projected to reach roughly 39% [119].

China's demand for natural gas will increase to 400×10^{27} m^3 by 2030, in contrast with the present demand, which is less than 200×10^{27} m^3. Henceforth, the National Energy Administration of China has proposed a proposal to achieve an annual production of biogas exceeding 30×10^{27} m^3 by 2030 [54]. Therefore, the 14th five-year plan provides a holistic preview of a renewable-dominated power system in the country's future. By 2025, electricity generation from renewable sources is anticipated to rise from 2.2 to 3.3 trillion kilowatt-hours, while non-fossil power generation should reach 39% compared to 34% in 2020 [41]. In the same context, the International Renewable Energy Agency IRENA [76] stated that China currently possesses the potential to use around 1 billion tons of agricultural and forestry residues for energy production. Additionally, an annual supply of 1.8 billion tons of livestock and poultry manure can be converted into biogas and organic fertilizer.

In Europe, based on a report published by the European Biogas Association, the biogas sector has experienced rapid growth, as evidenced by 18,843 operational biogas plants in 2021 compared to 6507 in 2009 [39]. In 2015, the European Union achieved a cumulative biogas production of 654 petajoules in primary energy, equivalent to over 18 billion cubic meters of natural gas [149]. Moreover, biomethane production has experienced significant expansion over the past decade, and the year 2021 witnessed the most substantial annual growth to date, with a supplementary 6 terawatt-hours or 0.6 billion cubic meters of biomethane production compared to the preceding year. This information provides insights into the proportion of each country's gas consumption that could be met through the utilization of biomethane, assuming the complete upgrading of all biogas resources within the country. The presented data unequivocally demonstrate that Denmark (24%) and Sweden (15%) are making substantial progress in substituting their natural gas consumption with biomethane [39]. Regarding policies, in 2021, the European Union set a taxonomy climate delegated act, stating that anaerobic digestion and biogas upgrading with gas grid injection are considered sustainable and low-carbon practices that encourage investments in the biogas industry [45].

China and Europe have made notable advancements in developing their respective biogas sectors (Table 2). However, several critical challenges necessitate attention and resolution [1]. Several factors contribute to the advancement of biogas production. One aspect that contributes to the efficiency of biogas production is the need for improved technical capabilities. Furthermore, the success of this subject relies on the need for efficient cooperation and coordination among diverse stakeholders. Moreover, a higher level of public awareness and acceptance of biogas as a possible and sustainable energy source must be cultivated [35].

Table 2 A comparison of the biogas industry in China and Europe, with reference to the worldwide data

Category	World	China	Europe	References
Number of biogas plants 2022	Not available	100,000	19,910	[39]
Energy from biogas 2021 (terawatt hours)	Not available	83.3	159	[39]
Primary feedstock	Agricultural waste and animal manure	Animal manure	Agricultural residue	[75]
Common utilization methods	Electricity and heat	Bio-natural gas and power production	Power production	[75]
Biogas market 2022 (billion US dollars)	58.2	10.7	24.6	[155–157]
Critical challenges	Global production does not meet the required target to achieve net-zero emissions	Most digesters are household units, and production expanded slower than planned	High production and utilization costs and competition with other renewables for bioelectricity production	IEA [75]

The biogas industry in China is becoming more popular due to the country's agricultural nature. Europe has advanced technologies regarding the use of crude biogas, highlighting the development and maturity of biogas technology. According to global statistics, China and Europe have the highest portion of the world's population

Biogas utilization for energy production

Biogas is increasingly acknowledged as a multifaceted and sustainable energy resource that can fulfill diverse energy requirements in both rural and industrial settings. Biogas's capacity to be transformed into energy, thermal output, and fuel enables it to fulfill a wide range of applications, consequently providing substantial environmental and economic advantages [21]. Biogas systems in rural regions can convert agricultural waste into energy, mitigating pollution and offering a dependable power source that improves living standards and economic prospects for local communities [54]. In urban environments, biogas enhances energy source diversification, diminishes dependence on fossil fuels, and alleviates urban pollution. Integrating biogas into the energy mix enhances air quality and the urban environment, thereby improving residents' quality of life [124]. The following sections provide detailed insights into these applications. The sections also highlight how biogas contributes to sustainable development and its essential role in enhancing environmental stewardship and economic resilience in various contexts.

Biogas utilization in rural areas

Specifically, the utilization of biogas for cooking fuel, domestic heating, and lighting demonstrates biogas adaptability and ecological, technical, and socio-economic effects in rural regions. Biogas provides a decentralized and environmentally beneficial option in rural communities with limited access to traditional energy sources [54]. As a fuel for cooking, biogas offers a readily available alternative to conventional biomass, therefore mitigating deforestation pressures and indoor air pollution. Furthermore, the utilization of biogas for residential heating enhances living standards, particularly in regions with colder temperatures. While using biogas for lighting not only increases productivity hours but also reduces dependence on non-renewable sources. This section provides a comprehension of how biogas, in addition to environmental advantages, acts as a catalyst for favorable transformation in rural areas.

Biogas as cooking fuel

The exploitation of biogas meets the energy requirements, environmental issues, and socio-economic progress, offering several advantages to rural areas around the globe. Rural regions sometimes have difficulties obtaining conventional energy sources [126]. Consequently, biogas as a decentralized energy alternative can reduce reliance on centralized power networks and provide rural families with a dependable supply of cooking fuel [54]. Biogas generation includes the anaerobic breakdown of organic waste, including agricultural waste, animal manure, and kitchen waste. This not only tackles waste management concerns but also converts organic matter into a valuable energy asset [161]. The use of biogas as a cooking fuel is a cost-effective technique that decreases household energy expenses, adding to the economic well-being of rural areas. Biogas initiatives have the potential to enhance rural development by generating employment prospects and encouraging local economies [126]. Furthermore, the act of selling excess biogas or by-products, such as organic fertilizers, has the potential to create supplementary revenue for rural communities.

Rural families in China widely use small-scale biogas digesters for cooking. These digesters employ organic waste to generate biogas for domestic cooking purposes [171]. Hence, the exploitation of biogas diminishes dependence on conventional biomass fuels such as wood and enhances the quality of indoor air, hence alleviating health hazards linked to traditional cooking techniques [149]. In addition, rural communities have advantages, such as decreased energy expenses and improved economic prospects by selling excess biogas or organic fertilizer generated during the digestion process. In Europe, biogas is included in the broader renewable energy framework, aiding in the achievement of sustainable energy objectives [149]. Biogas facilities commonly treat a combination of organic waste, such as agricultural waste and organic urban garbage. European nations prioritize the integration of biogas generation with agricultural operations by using digestate as a fertilizer.

Biogas for household heating

Using biogas fulfills community heating requirements, fosters energy self-sufficiency, and supports environmental and economic sustainability. Rural homes employ biogas for space heating, offering a clean and effective alternative to conventional heating techniques. Biogas stoves, heaters, and boilers provide a practical alternative for fulfilling the heating needs of individual households [121]. Furthermore, biogas is incorporated into district heating systems, in which a centralized facility generates and disseminates heat to several residences or structures. This strategy enhances the efficacy of biogas consumption, especially in heavily inhabited rural regions [58]. Several rural regions possess decentralized biogas facilities that function as energy centers for the local population. Rural regions use combined heat and power systems, sometimes referred to as cogeneration, to produce heat and electricity concurrently from biogas [63]. The generated heat can be used for residential heating or supplied to district heating networks. Furthermore, these systems promote environmental sustainability by diminishing dependence on fossil fuels and mitigating greenhouse gas emissions.

According to Hou et al. [63], China has adopted decentralized biogas facilities in rural regions, specifically for domestic heating. These facilities frequently use agricultural residues and animal dung as raw materials, offering a localized option for heating requirements [121]. Biogas-powered community-based heating systems have been used in rural Chinese villages. Through the utilization of a centralized biogas facility, several families may get advantages from a dependable and environmentally friendly heat source [102]. Whereas biogas has been successfully incorporated into district heating networks throughout Europe, benefiting both rural and urban regions [171]. Biogas-powered district heating systems offer an effective and environmentally friendly alternative for fulfilling the heating needs of various communities. Europe has been leading the way in the adoption of innovative technology for the production and use of biogas [130]. The implementation of high-efficiency biogas plants and modern heating systems enhances the success of biogas-based heating solutions.

Biogas for lighting

Biogas may be used as a fuel for lamps and lanterns, offering a pristine and effective lighting source. Biogas lamps are specifically engineered to use the energy from biogas in order to provide illumination, serving as a viable alternative to traditional lighting options [140]. Biogas-fueled lights can be put in households, improving visibility and prolonging working hours for a range of tasks. Moreover, biogas may be used to illuminate streets at the community level in rural regions. Public places may be illuminated using solar-powered biogas lamps or centralized biogas-powered lighting systems, therefore enhancing safety and promoting community well-being [19]. Biogas has the potential to be included in hybrid lighting systems, which involve the combination of several renewable energy sources. Rural communities can develop decentralized biogas facilities that generate both cooking fuel and biogas for illumination purposes [82]. This comprehensive strategy guarantees the versatile utilization of biogas, hence improving energy accessibility for diverse applications.

China and Europe provide unique perspectives on the effective use of biogas for lighting, demonstrating creative strategies and community-focused solutions. China has introduced biogas-powered lighting systems in rural homes [161]. Rural China is characterized by the widespread presence of decentralized biogas facilities, which function as energy centers at the community level. These plants generate biogas that serves both cooking and lighting purposes, helping to the achievement of universal energy access [82]. The Chinese government has proactively provided financial incentives and implemented rules to assist biogas plants. On the other hand, biogas has been included in Europe's district-wide lighting systems, encompassing both rural and urban regions. Biogas-powered centralized lighting systems have a role in the total energy combination inside communities. European areas prioritize the waste-to-energy idea, which includes lighting solutions [19]. Biogas produced from biological waste supports the ideals of a circular economy by offering sustainable illumination without imposing any additional environmental impact [172].

Biogas utilization in industrial areas

Within industrial sectors, the use of biogas serves as a symbol of sustainable ingenuity, offering a versatile solution to energy requirements. Biogas provides diverse uses, including power generation, heat creation, and fuel generation. These applications align with the ideas of circular economy and environmental responsibility [124]. Biogas is becoming an attractive choice as the industry looks for alternatives to traditional fossil fuels. The diversity of biogas applications in heat generation highlights the ability of biogas to provide an environmentally acceptable solution for a wide range of industrial operations. Furthermore, biogas serves as a fuel source that not only reduces carbon emissions but also promotes self-reliance in industrial complexes [112]. This section focuses on the applications of biogas as a renewable energy source in the industrial sector.

Biogas for electricity generation

The application of biogas in industrial settings has several benefits, such as ecological sustainability, waste disposal, and economic advantages. Commercial and industrial enterprises often use combined heat and power systems, sometimes called cogeneration, to optimize the efficiency of biogas consumption [82]. These systems can generate power and capture waste heat at the same time, which helps to enhance the overall energy efficiency in different industrial operations. Combined heat and power units have an efficiency of up to 90%, which is significantly higher than the efficiency of stand-alone systems, which typically range from 20 to 45%. Additionally, combined heat and power may generate both electricity and heat, with electricity accounting for 60% of the total output. Prior to using biogas in engines, the water vapor and hydrogen sulfide need to be eliminated from the biogas to prevent condensation and corrosion [1]. Numerous industrial complexes choose to have biogas power-producing plants located on their premises. On-site generating offers a distributed energy solution, decreasing dependence on external power sources and lowering transmission losses. Biogas power plants located in industrial regions can be linked to the electrical grid [102]. The excess electricity produced can be sent to the power grid, enhancing the total power supply and potentially generating cash through feed-in tariffs or power purchase agreements. Certain industrial operations produce organic by-products that are appropriate for the manufacture of biogas [63]. Industries may adopt a circular economic strategy by using these by-products, transforming waste into energy, and promoting sustainable practices.

China has observed extensive industrial biogas initiatives, namely, in the agro-industrial domain. Industries such as food processing, agriculture, and wastewater treatment use biogas to generate power on a large scale [4]. China prioritizes a waste-to-energy ideology, considering organic waste as a valuable resource. Within this framework, the implementation of favorable regulations, financial assistance, and rewards stimulate industrial investments in biogas initiatives, therefore promoting the attainment of overarching objectives related to sustainable development [38]. In Europe, a wide range of biogas uses in several industrial areas, including manufacturing and food and beverage production, have been introduced. Biogas is included in the energy composition of many sectors, enhancing the sustainability and diversification of their energy portfolio. Biogas, being a sustainable and low-emission energy source, should comply with regulatory standards and aid enterprises in achieving their sustainability goals [128]. China and Europe both acknowledge the economic feasibility of using biogas to generate power in industrial regions. Furthermore, the incorporation of biogas is in line with the objectives of environmental conservation in both China and Europe.

Biogas for heat generation

Industrial sectors employ biogas as a sustainable heat source for diverse operations, substituting traditional fossil fuels. Combusting biogas in industrial boilers or heaters offers a dependable and environmentally friendly source of heat. Raw biogas may be combusted directly in a boiler to produce heat with an efficiency of around 75–85% or higher [164]. Furthermore, the boiler may be used in combination with other equipment, such as steam turbines, to generate electricity, in addition to function in heat generation. Yin et al. [173] investigated three interrelated systems, one of which included a biogas boiler equipped with a backpressure turbine that had a power rating of 500 kilowatts. The process starts with the combustion of biogas to generate steam, which is then channeled into a steam turbine to generate power. The authors of the study concluded that the system was both ecologically and economically feasible. Biogas can be used in industries, such as food processing, manufacturing, and chemical production, to fulfill their own thermal needs [160]. Centralized biogas plants provide heat to various industrial regions, establishing an efficient and communal heating infrastructure. Biogas facilities frequently produce excess heat as a by-product during the anaerobic digestion process [7]. Waste heat recovery systems collect and use this heat for extra industrial heating requirements, hence improving overall energy efficiency.

China has extensive industrial biogas initiatives in areas, such as agriculture, food processing, and wastewater treatment. The Chinese government aggressively encourages the application of biogas in the industry through favorable regulations and programs [12]. Monetary rewards and governmental regulations motivate enterprises to embrace biogas as a heat source, which is in line with China's objectives for sustainable growth [161]. Additionally, European countries are adopting modern biogas technology where advanced anaerobic digestion systems and innovative combustion technologies are improving the efficiency and competitiveness of biogas for generating heat in industrial settings [130]. Industries in Europe are forced to adopt better energy choices due to strict environmental rules. Therefore, biogas is considered a way to reduce carbon emissions and promote sustainable waste management, thus supporting environmentally conscious industrial operations [1]. In both China and Europe, environmental management, economic feasibility, government cooperation, artistic creativity, and community engagement underscore the importance of biogas around the world as a sustainable source of industrial heating. Biogas for fuel generation

Industrial biogas projects frequently encompass the generation of bio-compressed natural gas, obtained from biogas, and function as an environmentally friendly substitute for conventional natural gas [116]. Additionally, this gas may be used in transportation, heating, and industrial operations. Several industrial regions have established refueling stations specifically for cars fueled by biogas. This encompasses a collection of trucks, buses, or other types of vehicles that operate using bio-compressed natural gas derived from industrial biogas plants [164]. Furthermore, advanced biogas initiatives investigate the creation of hydrogen via a process referred to as biogas reforming since biogas can be used to produce hydrogen, which can then be employed as a fuel in fuel cells, offering an environmentally friendly energy alternative [116]. This form of energy may be used in several sectors, including chemical manufacture, industrial production, and medicines, as well as power specialized equipment and machinery. In addition, refined biomethane can be introduced into the natural gas network. Subsequently, this introduced biomethane, which may be used as a source of energy by various enterprises or even residential areas that are linked to the gas network [34].

China thoroughly uses bio-compressed natural gas derived from biogas for transportation and industrial applications. Biogas-powered cars in the transportation industry yield decreased emissions, hence providing a positive impact [56]. Europe has a complete strategy for using biogas, ranging from bio-compressed natural gas for vehicles to injecting biomethane into the gas infrastructure [25]. Europe's dedication to technical progress is seen via the implementation of advanced anaerobic digestion systems, biogas purification, and injection into the gas grid [149]. Although there are variations in how commercialized biogas use for fuel generation is implemented in different regions, there are certain shared approaches in China and Europe that aim to improve and maximize the use of biogas in order to reduce dependence on fossil fuels.

In summary, the utilization of biogas in both rural and urban areas can facilitate a fundamental change in energy consumption patterns. Biogas is a powerful catalyst in rural regions as an environmentally friendly fuel for cooking, supplies heating to households, and offers lighting to houses. This not only tackles the issue of energy poverty but also reduces the dependence on conventional, ecologically detrimental fuels. The influence extends to urban settings where biogas is included as a fundamental component of industrial activities. Industries use biogas to generate power, diminishing their carbon footprint and promoting a more environmentally friendly energy system. Bioheat generation is crucial for supporting a range of industrial activities that align with sustainability goals. Furthermore, the utilization of biogas as a fuel in industrial settings fosters energy autonomy, hence reducing reliance on finite resources. In this context, Fig. 4 summarizes the main pathways of using biogas on both rural and industrial levels for producing different energy products.

Digestate as a nutrient-rich substance

Anaerobic digestion can be a sustainable approach for biogas production, whereas digestate can be used as a soil amendment abundant in nutrients [7]. Naturally, digestate is a complex mixture of organic and inorganic compounds, including nitrogen, phosphorus, potassium, and other micronutrients [134]. The nutrient content of digestate varies depending on the feedstock used, the type of anaerobic digestion process, and the degree of separation of solids and liquids. However, digestate is a valuable source of nutrients that can help to improve soil fertility and plant growth [84]. The nutrient composition of digestate exhibits variability, which is contingent upon factors, such as the feedstock employed, the specific anaerobic digestion technique employed, and the extent to which solid and liquid components are separated [113]. In a broad sense, digestate possesses significant value as a nutrient-rich resource, capable of enhancing both soil fertility and plant growth [163].

One of the primary advantages associated with the utilization of digestate as a fertilizer is digestate ability to serve as a long-lasting source of nutrients, gradually released and absorbed by plants over an extended duration [137]. In contrast with synthetic fertilizers, which can potentially induce nutrient leaching and pollution, the utilization of digestate, when employed responsibly, poses a reduced risk of environmental detriment [61]. In addition to the nutritional composition, digestate also encompasses organic matter, which has the potential to enhance soil structure and augment water retention capabilities [123]. The utilization of digestate as a soil amendment has the potential to mitigate soil erosion, enhance soil fertility, and augment crop productivity [5].

Digestate production

The generation of anaerobic digestate involves a captivating process in which microbes, organic materials, and ambient conditions interact in a complex manner, resulting in a remarkable metamorphosis [88]. The anaerobic digestion process starts by introducing organic feedstock, which

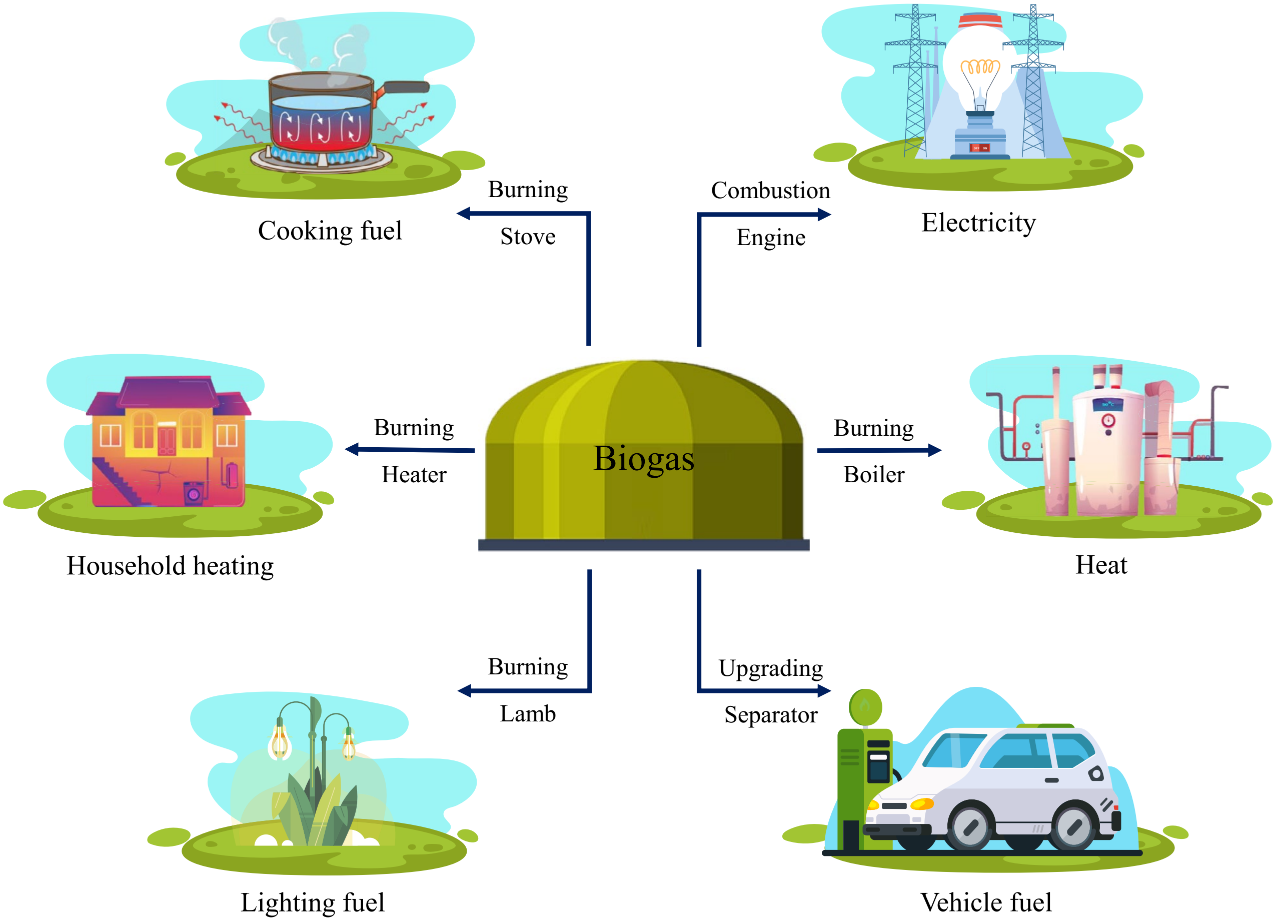

Fig. 4 Common uses of crude biogas as a source of different energy forms. Biogas has a significant promise for providing environmental advantages and economic feasibility in several industries. The use of biogas for cooking fuel, residential heating, and lighting demonstrates biogas's versatility in environmental and socio-economic impacts in rural areas. At the same time, biogas offers a wide array of applications, such as electricity production, heat generation, and fuel manufacturing

can vary from agricultural leftovers to organic waste, into anaerobic digesters. Microorganisms within these regulated, anaerobic habitats coordinate an intricate sequence of metabolic incidents [90]. The anaerobic digester uses a consortium of microorganisms, comprising bacteria and methanogens, to decompose complex organic molecules [111]. The primary hydrolysis step transforms complex polymers, such as carbohydrates and lipids, into more basic molecules. Subsequently, acidogenesis occurs, resulting in the production of volatile fatty acids. Acetogenesis is the process in which acetate, hydrogen, and carbon dioxide are produced, which sets the stage for the subsequent methanogenesis phase, during which methane is produced [53, 111]. Although biogas is the main product of anaerobic digestion, digestate still contains valuable nutrients, organic matter, and microbial biomass. The composition of digestate is contingent upon the characteristics of the feedstock and the effectiveness of the anaerobic digestion process [44]. The resultant digestate is a diverse combination that includes both liquid and solid components. The liquid portion, often obtained by separating digestate from the solid using dewatering methods, includes dissolved nutrients, while the solid portion consists of organic wastes, which can be used in agriculture [8].

Digestate management

The separation of liquid and solid fractions is the first step of digestate management and is a crucial step in the whole management system. There are several techniques available for accomplishing this task, including centrifugation, screw press, and belt filter presses [103]. The liquid fraction can undergo additional treatment techniques, such as membrane filtration or reverse osmosis, in order to eliminate contaminants and pathogens, as well as to reclaim valuable nutrients [103]. The solid fraction possesses potential applications, such as a fertilizer or soil conditioner; however, supplementary treatment is needed, such as composting, to adhere to established regulatory standards [103, 162].

Ensuring adherence to regulatory requirements is a crucial element in the management of digestate, and the handling, storage, and application of digestate should be subjected to country-specific and regional regulations and protocols [92, 147]. In the context of the European Union, the utilization of digestate as a fertilizer is subject to compliance with specific quality standards, as stipulated by the fertilizing products regulation (EC) No. 2003/2003 [46]. Moreover, in China, the liquid digestate undergoes treatment through a wastewater treatment system and is subsequently discharged upon meeting the requisite criteria outlined in the Integrated Wastewater Discharge Standard (GB 8978–1996). Similarly, when using liquid digestate as a fertilizer, one important thing is to ensure that digestate quality adheres to the standards outlined in the document titled "Standard of Water-soluble Fertilizers containing humic acids" (NY 1106–2010) [95].

Legislative policies for digestate management

The legislative regulations regarding digestate management are crucial in determining sustainable practices in the biogas industry. Governments and environmental authorities globally are progressively acknowledging the significance of regulating the management, processing, and usage of digestate, which is a nutrient-dense residue produced by anaerobic digestion [103]. These policies aim to tackle environmental issues, promote the secure and accountable use of digestate, and foster the concepts of circular bioeconomy. Legislative frameworks often determine the acceptable techniques for applying substances, considering variables, such as the kind of crops, soil conditions, and proximity to bodies of water in order to avoid the runoff and pollution of nutrients [112]. Furthermore, rules may establish criteria for the processing of digestate to decrease the presence of harmful microorganisms and unwanted plant seeds, guaranteeing digestate suitability for use in farming methods [3]. These policies include incentive programs, subsidies, or tax credits to promote the adoption of sustainable digestate management techniques. This aligns with the broader objectives of lowering dependence on synthetic fertilizers and minimizing environmental consequences [146]. The dynamic nature of these regulations demonstrates continuous initiatives to achieve a harmonious equilibrium between encouraging the advantageous use of digestate in agriculture and protecting ecosystems and public health [29, 112]. As biogas business progresses, regulatory frameworks are expected to adjust to technological improvements, research discoveries, and shift agricultural and environmental concerns.

In China, rules regarding the management of digestate are becoming more in line with the country's high-level goals for environmental sustainability and the creation of a circular bioeconomy. The country has acknowledged the significance of the practical usage of organic waste and has enacted legislation to guide managing digestate [131]. For instance, the action plan for the prevention and control of water pollution emphasizes strategies to enhance the efficient use of livestock and poultry manure. This plan promotes the use of technology, such as anaerobic digestion, to treat this waste. Also, by 2020, there will be a reduction in groundwater overdraft and preliminary control of aggravated groundwater contamination [154]. The 13th five-year plan for the development of livestock and poultry breeding prioritizes the proper management and usage of manure resources, promoting a transition toward environmentally sustainable farming methods. In addition, regional policies, particularly in Shandong Province, have established precise objectives for the implementation of anaerobic digestion projects in order to manage organic waste efficiently [109]. Moreover, the Chinese ministerial standards of organic fertilizers (NY/T 525-2021) were officially announced in 2021. When compared to this benchmark, biofertilizers made from digestate require more organic matter to meet the organic matter requirements of commercially accessible biofertilizers. Also, the Chinese ministerial standard digestate fertilizer (NY/T 2596-2022) was published in 2022. Based on this criterion, digestate can solely be used on fields in accordance with the guidelines for applying livestock and poultry manure. Consequently, commercializing digestate as a product is challenging [55]. These efforts contribute to the remarkable data of the increasing number of biogas plants and anaerobic digestion facilities in China, demonstrating the country's dedication to sustainable waste management methods and the production of renewable energy [26].

Similarly, the European Union has established a comprehensive system of directives and rules, compelling member states to adopt policies. Several initiatives have been launched, such as the nitrates directive, which establishes strict criteria for the use of organic fertilizers, such as digestate, to reduce the potential for water contamination caused by nitrates. These pertain to bodies of water that have become eutrophic or might have a nitrate concentration exceeding 50 mg/l as a result of agricultural operations [47]. The standard agricultural policy offers monetary assistance for the implementation of environmentally friendly agricultural methods. On June 1, 2018, the European Commission proposed common agricultural policy reform legislation. On December 2, 2021, the formal acceptance of the common agricultural policy was made, and the strategic plans began in January 2023. Every strategic plan will be evaluated annually by the commission until 2027. Certain member states, such as Germany and the Netherlands, have included the management of digestate in their national agri-environmental programs (European [48]). On the level of countries, several laws have been issued in this regard, such as Reichsausschuss für Lieferbedingungen quality assurance in Germany, the British Standard Institution publicly available specification (BSI PAS 110) in the UK, and SPCR 120 in Sweden [55]. In addition, the waste framework directive provides standards for the management and reuse of organic waste, highlighting the crucial importance of anaerobic digestion in the circular bioeconomy. The regulatory focus on anaerobic digestion plants in Europe is seen in the increasing number of such facilities. These plants play a vital role in recycling organic waste and promoting sustainable agricultural practices [49]. The European method of managing digestate exemplifies the successful integration of environmental objectives with agriculture strategies.

Environmental impact assessment

Environmental impact assessment is a systematic process employed to identify, predict, evaluate, and mitigate the potential environmental effects of proposed projects, policies, or activities. According to Hong et al. [62], environmental impact assessment offers complete knowledge of the possible environmental consequences that a project may have before being put into action. This approach promotes the development of sustainable practices [9]. Life cycle assessment is one of the most extensively used methodologies for environmental impact assessment. This type of assessment may be used to quantify environmental emissions throughout the life cycle of various processes, which will be detailed in the following sections [141].

Life cycle assessment is a systematic approach that allows for the quantitative analysis of the environmental consequences linked to a product over the whole life cycle, from production to disposal. This approach adheres to the standards set out by the International Organization for Standardization [77, 78]. Life cycle assessment has emerged as the preeminent and widespread method globally for measuring and contrasting the ecological consequences of various products. Life cycle assessment may be used to evaluate the environmental sustainability of agricultural waste for biogas generation and the use of crude biogas for energy production [7, 9].

Life cycle assessment tool has a general framework, and the implementation of such studies includes several stages, i.e., (i) definition of the goal and scope of the study, (ii) defining the system boundaries, (ii) collection and adaptation of life cycle inventory, (iv) conducting the life cycle impact assessment, and (v) results interpretation [141]. These four phases are explained in the following subsections. Figure 5 shows the general framework of life cycle assessment in accordance with the goal of the current study, including extraction of agricultural waste as raw material, transportation of this waste, anaerobic digestion, biogas production and utilization, and end of this life cycle.

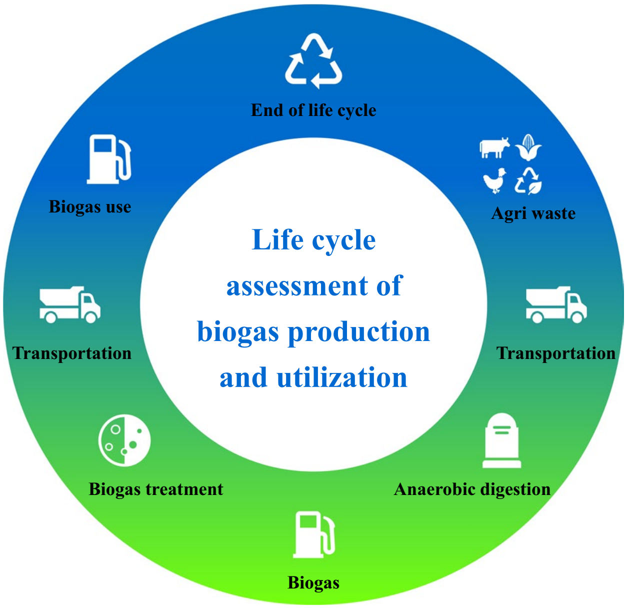

Fig. 5 General framework of life cycle assessment of biogas production and utilization. The overall structure of the life cycle aligns with the objective of the present research, including the collection of agricultural waste as a primary resource, the transportation of this waste, the process of anaerobic digestion, the generation and consumption of biogas, and the conclusion of this life cycle

Goal and scope definition

Defining the objective involves answering several essential inquiries, such as the purpose behind doing the life cycle assessment. What are the goals we want to achieve through life cycle assessment studies? Who is the intended target demographic? The following questions relate to determining the principal aim of life cycle assessment studies as delineated by Lee and Inaba [93]. The selection of the functional unit is crucial, often quantified as the biogas yield per metric ton of agricultural waste or per unit of energy generated [141]. The scope often delineates the parameters of the evaluation, including the particular categories of agricultural waste, biogas production systems, and biogas utilization processes to be considered [51]. The evaluation should include the choice of certain agricultural waste categories, such as crop residues, manure, or food waste, and consider various biogas generation techniques, including wet and dry anaerobic digestion systems. Moreover, setting unique system boundaries is crucial for completing a comprehensive life cycle assessment. In order to conduct a comprehensive life cycle assessment, clear system boundaries should include all pertinent stages and processes associated with the production of biogas from agricultural waste and the energy generation from crude biogas [159].

Life cycle inventory

During the life cycle inventory phase of biogas generation by anaerobic digestion of agricultural waste, it is essential to meticulously document all pertinent inputs and outputs at every step of the process. This inventory contains information on energy consumption related to agricultural activities, feedstock transportation, and the energy used in the anaerobic digestion process, including heating and mixing in the biogas reactors [142]. The lack of readily available inventory data remains a major obstacle to the deployment of life cycle assessment. Nevertheless, several databases have been constructed in recent decades to facilitate life cycle inventory and minimize the repetition of data collection [141]. This involves closely monitoring energy consumption, emissions, and resource use at each stage, including activities, such as planting, harvesting, transportation, anaerobic digestion for biogas generation, and processing of biogas conversion [15]. When creating an inventory for biogas production, all inputs, such as agricultural waste feedstock, water, and energy required for the anaerobic digestion process, should be included. Also, biogas can be used as a source of energy production via different conversion methods, as reported by Alengebawy et al. [7].

Life cycle impact assessment

Life cycle impact assessment assesses the possible environmental effects that have been discovered in the life cycle inventory. This involves evaluating the possibility of global warming, eutrophication, acidification, and other pertinent effect categories [31]. Life cycle impact assessment facilitates the comprehension of the magnitude of environmental loads linked to the whole process. The life cycle impact assessment incorporates evaluating and quantifying the possible environmental consequences linked to agricultural waste biogas generation and biogas use [7]. The impact evaluation for biogas production might examine lowering greenhouse gas emissions compared to alternative waste management techniques, energy generation and fossil fuel substitution, and air and water pollution. The purpose of the life cycle impact assessment for biogas generation from agricultural waste is to measure and evaluate the possible environmental effects linked to every stage of the system. One important area that has to be evaluated is the decrease in greenhouse gas emissions by capturing and using methane, which is a powerful greenhouse gas [9].

Results interpretation

Interpreting life cycle assessment data involves deriving conclusions and suggestions from the obtained findings. This stage evaluates the trade-offs and hotspots found in the research, offering valuable insights into areas that may be improved to achieve more sustainable operations [32]. Interpreting the results requires assessing and interpreting the life cycle assessment findings for the generation of biogas from agricultural waste and energy recovery. This requires the identification of the notable environmental consequences linked to each step of the life cycle, comparing various scenarios or processes, considering trade-offs, and resolving uncertainties [87]. This stage can facilitate decision-making, enhance process optimization, and foster the creation of sustainable agriculture practices.

Recent progress on life cycle assessment of biogas systems

An increasing emphasis has been placed on researching the environmental impacts associated with the conversion of agricultural waste into biogas. Life cycle assessment is widely acknowledged as a crucial tool for comprehensive evaluations of the environmental impacts of diverse operations [127]. This section presents a thorough overview of recent developments in life cycle assessment research, with a particular focus on the production of biogas from agricultural residues and subsequent use of this crude biogas. Table 3 presents a succinct outline of significant findings from particular investigations related to biogas systems.

In summary, life cycle assessment is an effective tool for quantifying and evaluating the environmental impact associated with anaerobic digestion and related processes. Recent life cycle studies have provided useful information into the environmental sustainability of producing biogas from agricultural residues and their use for electricity generation. Multiple studies have emphasized the potential of biogas as a renewable energy source with positive environmental characteristics, such as lower greenhouse gas emissions and fewer environmental effects compared to traditional energy sources. In addition, life cycle assessment studies have revealed potential areas for increasing biogas production systems, including optimizing the selection of feedstock, improving digester performance, and investigating new energy conversion technologies.

Emissions trading and sustainability

Emissions trading is a novel market-oriented strategy designed to decrease the release of greenhouse gases. This process offers financial incentives to encourage companies to

Table 3 Most recent results of life cycle assessment investigations concerning biogas production and utilization in select European countries and China

Study area	Biomass type	Functional unit	Study model	Conversion method	Products	Main findings	References
China	Corn stover and animal manure	1 megawatt-hour of electricity	Gate-to-grave	Anaerobic digestion, purification, combustion, and drying	Biogas, electricity, and biofertilizer	Corn stover biogas project had a higher net energy efficiency (763.9 megawatt-hour/functional unit), while the dairy manure biogas project had a greater reduction in greenhouse gas emissions (5541.4 kg CO_2-eq/functional unit)	Sun et al. [79]
China	Swine manure	1 ton fresh swine manure	Not available	Separation, anaerobic digestion, and composting	Biogas and biofertilizer	Solid–liquid separation of swine manure reduced global warming, eutrophication, acidification, and human toxicity by 56%, 273%, 83%, and 81%, respectively	Zhang et al. [175]
Finland	Agricultural waste	Not available	Gate-to-grave	Anaerobic digestion, separation, combustion, pelletization, evaporation, and ammonia stripping	Biogas, power, and biofertilizer	The emission reductions were 67%–74% and 13%–30%, respectively, when biogas was employed in combined heat and power production unit	Lehtoranta et al. [94]
Italy	Dedicated and discarded biomass	1 kilowatt-hour of electricity	Cradle-to-gate	Anaerobic digestion, chipping, and refining	Electricity and heat	Out of all the types of bioenergy, solid biomass is considered the most ecologically benign choice since this biomass does not depend on specific crops. In contrast, biogas has the most significant environmental effect	Fiorentino et al. [52]

Table 3 (continued)

Study area	Biomass type	Functional unit	Study model	Conversion method	Products	Main findings	References
China	Rice straw	1 metric ton dry rice straw	Field-to-gate	Anaerobic digestion, gasification, and briquetting	Biogas, briquette fuel, and syngas	Three scenarios had net positive energy and negative greenhouse gas balances. Syngas is the most sustainable alternative, followed by briquette fuel and biogas	Alengebawy et al. [9]
China	Pig manure	1 metric ton pig manure	Not available	Anaerobic digestion, combustion, and separation	Heat, electricity, biomethane, and biofertilizer	The downstream approach of digestate fractionation and microalgae culture would have lesser implications on ecosystem quality, human health, and climate change	Duan et al. [37]
Germany	Grassland biomass	1 hectare grassland	Cradle-to-grave	Anaerobic digestion, briquetting, and combustion	Bioenergy	Compared to anaerobic digestion, integrated generation of solid fuel and biogas from biomass was preferable due to the greater primary energy and environmental savings	Joseph et al. [81]
UK	Biodegradable waste	1 kg of biodegradable feedstock	Gate-to-grave	Anaerobic digestion, gasification, and upgrading	Biomethane and biogas	The supply chains for biogas and biomethane yield an average of 51%–70% and 42%–65% reductions in greenhouse gas emissions compared to midstream natural gas and all hydrogen production pathways, respectively	Bakkaloglu and Hawkes [20]

Table 3 (continued)

Study area	Biomass type	Functional unit	Study model	Conversion method	Products	Main findings	References
China	Pig manure	1 ton pig manure	Not available	Dewatering, anaerobic digestion, and composting	Biofertilizer and clean water	Composting is responsible for the highest contribution of greenhouse gases in biological treatment, anaerobic digestion, and composting, accounting for 77%, 95%, and 79%, respectively	Liu et al. [96]
China	Corn stover	1 megajoule heat energy	Cradle-to-gate	Anaerobic digestion, gasification, and pelletization	Biogas, stover pellets, and syngas	Using stover pellets is more detrimental to human health and the ecosystem as a whole while causing less damage to resource depletion than using stover biogas	Su et al. [158]
EU-27	Biowaste	1 megawatt biomethane	Cradle-to-gate	Anaerobic digestion and gasification	Biomethane	Syngas road has higher carbon utilization and better environmental performance than biogas roads; however, expanded sensitivity analysis indicates different findings for alternate plant layouts and energy mix	Ardolino and Arena [14]
Turkey	Agricultural waste	1 megawatt-hour electricity and heat	Cradle-to-grave	Anaerobic digestion, combustion, and separation	Heat, electricity, and biofertilizer	Using feedstocks with high solid content and biogas output, such as organic waste and chicken manure, reduced the environmental impacts compared to natural gas and grid power	Balcioglu et al. [21]

Table 3 (continued)

Study area	Biomass type	Functional unit	Study model	Conversion method	Products	Main findings	References
China	Crop residue	1 kg lignocellulosic crop waste	Not available	Composting	Biofertilizer	In all impact categories, with the exception of photochemical oxidation, the rice straw scenario exhibited the least adverse environmental impact in comparison with the other scenarios	He et al. [60]
China	Swine slurry	2136 ton/year swine manure	Gate-to-grave	Large-scale and household anaerobic digestion, combustion, and sedimentation	Heat, electricity, and biofertilizer	Global warming and photochemical oxidation were greater in large-scale plants, whereas the household plant was more susceptible to eutrophication, acidification, and human toxicity	Wang et al. [169]
Italy	Agro-industrial waste	1 ton available biomass	Cradle-to-gate	Anaerobic digestion, combustion, and separation	Heat, electricity, and biofertilizer	The results indicated that anaerobic digestion of agro-industrial feedstocks avoids greenhouse gases and helps to circular economy organic matter cycles by valorizing waste and providing renewable energy	Valenti et al. [166]
UK	Spent coffee grounds	1 ton spent coffee grounds	Cradle-to-grave	Anaerobic digestion, combustion, and incineration	Electricity, heat, biofertilizer, and glycerin	The most ecologically beneficial alternative is incineration of spent coffee grounds, which has net-negative consequences in 14 of 16 categories, followed by direct land application with 11 net-negative impacts	Schmidt Rivera et al. [150]

There is a growing focus on studying the environmental effects linked to the transformation of agricultural waste into biogas. Life cycle assessment is generally recognized as an essential method for undertaking thorough assessments of various environmental consequences embrace cleaner and more sustainable practices [100]. Emissions trading is crucial in promoting environmental sustainability and facilitating the shift to a low-carbon economy in the conversion of agricultural waste to biogas [28]. Within the context of biogas generation from agricultural waste, emissions trading presents many possibilities for encouraging and compensating the mitigation of greenhouse gas emissions. Several credits can be obtained from different aspects of the biogas production process, such as considering biogas as a renewable energy source, carbon trading via mitigating carbon dioxide emissions, and credits from methane capture and utilization.

Emissions trading of biogas production

Renewable energy credits play a crucial role in incentivizing energy generation from renewable sources, such as biogas. They enable the identification, exchange, and commercialization of the ecological advantages derived from producing sustainable energy [136]. Renewable energy credits are granted for each megawatt-hour of electricity generated from a renewable source, such as biogas. Credits are certifications that confirm the environmental characteristics of renewable power, such as lower carbon emissions and the replacement of fossils [104]. Sales of these credits enable project developers to recoup initial investment expenses and fund the growth of further renewable energy projects. For example, biogas plants that produce electricity may earn revenue by selling the electricity to the power grid, and the renewable energy credits linked to that electricity. The dual-income model is particularly appealing in areas where the price of electricity alone may not adequately justify the substantial initial expenses [50]. Renewable energy credits not only help the growth of renewable energy but also contribute to the overarching objective of lowering greenhouse gas emissions. Biogas production has a double advantage: Biogas produces renewable energy and reduces methane emissions from organic waste [152]. Methane is captured and transformed into biogas, which may be used for the production of power. Renewable energy credits are useful in both voluntary and compliant carbon markets since they not only signify the renewable source of energy but also include the emissions reduction benefit [136]. The decrease in methane emissions may be measured and valued via emissions trading. Industries or governments needing to offset their emissions or meet legal criteria may purchase the created carbon credits [30].

Carbon emissions trading, also known as "cap-and-trade" systems or "carbon markets," aims to decrease the emission of carbon dioxide and other greenhouse gases by limiting overall emissions. This system permits trading emission allowances or carbon credits [28]. This system provides financial motivation for enterprises to decrease their emissions. Businesses that successfully reduce their emissions below the predetermined limit are able to sell their surplus emission permits to other companies that have exceeded their emission limitations [135]. This is a market-oriented strategy for managing pollution, promoting economic efficiency, and encouraging environmental accountability. Biogas production is crucial in this context, especially for efficiently mitigating methane emissions, a potent greenhouse gas with far greater global warming potential than carbon dioxide [101, 167]. Methane emissions often result from the breakdown of organic materials, such as agricultural waste, in oxygen-deprived environments. To avoid the escape of methane into the atmosphere, organic waste is sent to biogas plants, where methane is absorbed and turned into electricity. This procedure produces sustainable energy and decreases greenhouse gas emissions [10]. The carbon emissions prevented by collecting and using methane in biogas projects may be measured and converted into carbon credits, which can then be sold or exchanged in carbon markets [135].

Circular bioeconomy

The circular bioeconomy loop digestate valorization and application is an integrated method that optimizes resource efficiency, reduces waste, and fosters sustainability [172]. This methodology establishes a self-contained system in which digestate is converted into valuable products, therefore diminishing environmental consequences and fostering a circular and regenerative economic model [57, 112]. In this context, rather than discharging digestate as waste material, other sustainable methods can be employed in diverse advantageous ways to treat this digestate and produce value-added products [29]. Digestate contains vital nutrients and organic substances that enhance the composition of the soil, the capacity to retain water, and the availability of nutrients. The circular bioeconomy loop is completed by using biofertilizers in agriculture since they allow for the return of vital nutrients to the soil from waste generated by agricultural operations [137].

Additionally, digestate can be used as a raw material for manufacturing bioproducts and biochemicals. Using biorefinery techniques, digestate can be transformed into several high-value products [85]. These products include bioplastics, biofuels, platform chemicals, or other bio-based materials. When digestate is used as a raw material in such an approach, the circular bioeconomy expands the scope beyond the energy industry, facilitating the creation of other environmentally friendly and renewable products [103]. The combination of different methods for digestate valorization has synergistic effects that strengthen the circular bioeconomy loop. For instance, integrated approaches can be valuable to treat digestate, such as ammonia stripping coupled with nutrient extraction [8], in addition to the multifaceted use of liquid digestate as a medium for microalgae cultivation then use these algae for energy production [88]. Furthermore, the nutrients included in digestate can be used directly to augment the development of biomass crops, which can then serve as feedstock for biogas generation, thus further completing the cycle [114]. Figure 6 depicts integrating anaerobic digestion and digestate valorization approaches with the closed-loop circular bioeconomy concept.

Perspective

As anaerobic digestion continues to gain recognition as a sustainable method for treating waste and generating energy, there are numerous promising opportunities and directions for future research and development. Further investigation is required to optimize anaerobic digestion processes and enhance efficiency by exploring future perspectives such as substrate pretreatment, reactor design, and process monitoring and control. For constant biogas generation, anaerobic digestion systems must be stable and resilient, especially under dynamic operating circumstances. Innovative substrates and co-digestion should be explored to increase biogas output and diversify feedstock alternatives. This involves testing industrial waste streams and new feedstocks, including algae, microorganisms, and lignocellulosic materials. Also, additional investigation is required to improve our comprehension of the anaerobic digestion process, specifically regarding the interplay between microbial communities and different feedstock compositions. Also, combining anaerobic digestion with other renewable energy technologies, such as solar and wind power, might provide a more robust energy infrastructure. This approach has the potential to improve energy security, ensure grid stability, and enhance overall system efficiency, all while minimizing adverse environmental impacts. Promoting the integration of power plants with the anaerobic digestion process can enhance the overall efficiency of the entire process since the direct use of crude biogas does not fulfill the future target regarding carbon neutrality. Finally, the high production and utilization costs and competition with other renewables for power generation are critical issues that must be addressed.

Conclusion

This review has presented an extensive investigation of anaerobic digestion as a well-established method for waste management and the generation of sustainable energy. Biogas production, specifically from agricultural waste, and biogas utilization within a circular economy framework are explained in detail. The review presents a comprehensive overview of the conventional and sustainable

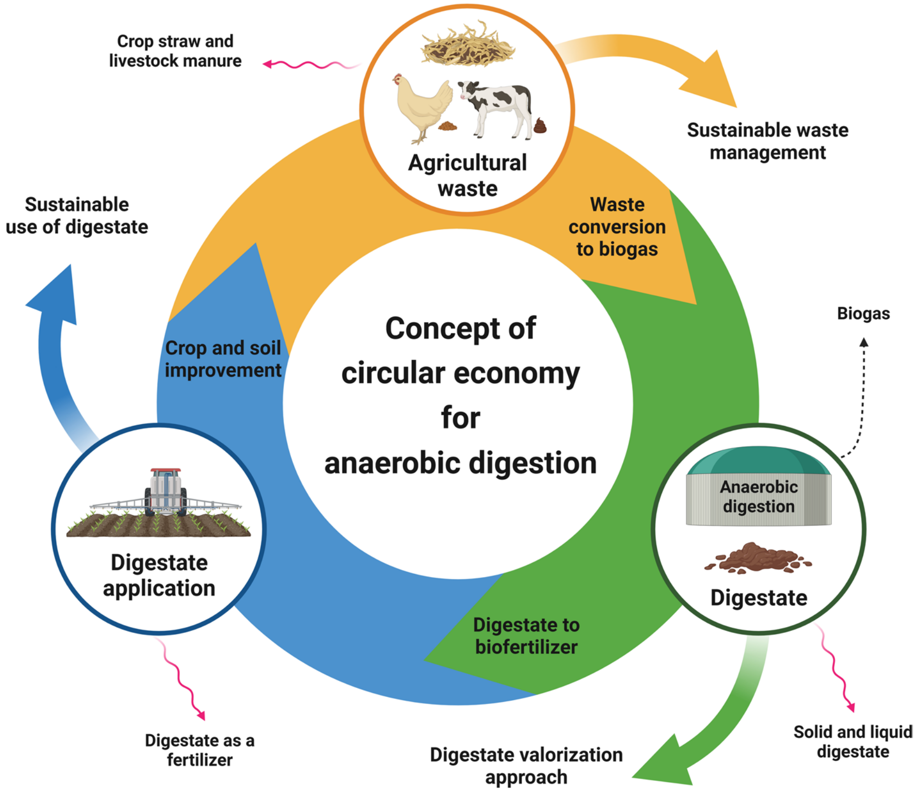

Fig. 6 Integrated biogas production and digestate valorization in line with a circular bioeconomy framework. In this approach, biogas can be produced as a primary product via anaerobic digestion of agricultural waste. Additionally, instead of disposing of digestate as waste, alternative sustainable methods can treat and convert this digestate into valuable products. This integration closes the loop to achieve the circular bioeconomy principle

energy sources, emphasizing the environmental impacts of conventional energy and the capacity of bioenergy to alleviate emissions, substantiated by data from China and Europe. This analysis focuses on the growth of the biogas sector in these areas, highlighting its significance in converting agricultural waste into usable energy. In addition to examining biogas production, the review also explored the use of biogas for energy generation, particularly in rural and industrial environments. Case studies conducted in China and Europe have provided valuable insights into different aspects of biogas production and utilization. These studies have demonstrated that biogas has significant potential as a renewable energy source and may be a viable solution to the waste crisis. The review provides a detailed analysis of emissions trading and sustainability aspects related to biogas production. This includes examining renewable energy credits, carbon emissions trading, and methane capture. The article discusses the role of biogas in promoting a circular bioeconomy, highlighting its contribution to addressing global challenges in waste management, energy stability, and environmental sustainability. Overall, this review enhances our understanding of anaerobic digestion and biogas utilization, emphasizing their importance in handling worldwide issues concerning waste management, energy stability, and environmental sustainability.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval AIO declares that he is the Editor of Environmental Chemistry Letters.

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