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Review

A critical review for the impact of anaerobic digestion on the sustainable development goals

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ABSTRACT

Anaerobic Digestion (AD) technology emerges as a viable solution for managing municipal organic waste, offering pollution reduction and the generation of biogas and fertilisers. This study reviews the research works for the advancements in AD implementation to effectively impact the UN Sustainable Development Goals (SDGs). Furthermore, the study critically analyses responsible waste management that contributes to health and safety, elevating quality of life in both rural and urban areas and, finally, creates a map of AD outputs onto all 17 SDGs. Finally, the assessment employs the three sustainability pillars (i.e., economic, environmental, and social perspectives) to examine the direct and indirect links between AD and all 17 UN SDGs. The findings reveal substantial progress, such as poverty reduction through job creation, bolstering economic growth (SDGs 1, 8, 10, 12), enhancing agricultural productivity (SDG 2), advancing renewable energy usage and diminishing reliance on fossil fuels (SDG 7), fostering inclusive education and gender equality (SDGs 4, 5, 9), combating climate change (SDG 13), transforming cities into sustainable and harmonious environments (SDGs 11, 16, 17), and curbing environmental pollution (SDGs 3, 6, 12, 14, 15). Nonetheless, the study highlights the need for further efforts to achieve the SDG targets, particularly in part of liquid and solid fertilisers as the AD outputs.

1. Introduction

Rapid population growth, economic development and urbanisation have resulted in the generation of various types of wastes, especially municipal organic wastes (WBA, 2021). The generation and mismanagement of this waste pose a multitude of challenges, encompassing environmental problems such as clogging of drains (leading to flooding), pollution and ecosystem destruction, ocean contamination and transmission of diseases. These issues also extend to social hazards including adverse impacts on human health and depletion of valuable human resources. Furthermore, there are economic loss such as diminished property values, decreased tourism and escalated clean-up costs, particularly when solid waste is poorly managed (Kaza et al., 2018). Consequently, municipal organic waste is recognised as a critical sustainability challenge, a fact underscored by its inclusion in the United Nations Sustainable Development Goals (SDGs) (Soni et al., 2022).

Municipal organic waste i.e., food residuals and green waste is found in large quantities in many developing countries, including Africa, the Middle East, parts of South America and Southeast Asia, as shown in Fig. 1a. The amount of municipal organic waste generated per capita, shown in Fig. 1b, is significant in Europe, North and Central America and Oceania. Thus, there is a high demand for applying municipal organic waste management technologies, including anaerobic digestion (AD) technology, composting, landfill and incineration as a vital and essential approach worldwide (Fazzo et al.,2020). Landfills are the least preferred and unsustainable practice due to their lack of recovery and recycling potential, adverse impact on soils, water pollution and significant contribution to global warming (Masalegooyan et al., 2022). Alternatively, composting and incineration are observed to be more effective, but they may suffer from odour and past issues, large space requirements, air pollution, residue management, and public concerns (Wainaina et al., 2020).

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On the other hand, AD has garnered attention as a promising method for breaking down organic waste materials. AD is also a multi-step biological and chemical process driven by a consortium of microbes, accompanied by a series of metabolic pathways. In the absence of oxygen, this process transforms organic waste materials through the actions of diverse microbial populations (Patel et al., 2023). This process yields valuable byproducts such as biogas and other energy-rich organic compounds and can be implemented on various urban scales, ranging from micro to macro levels (Patel et al., 2021).

Recently published works have reviewed the application, technological enhancement, advantages and challenges of using AD and outlined attempts to raise economic, environmental or social aspects of AD (Walker et al., 2017; AL-Huqail et al., 2022). However, the AD role in implementing and balancing SDGs remains uncertain. This is particularly significant because SDGs are approaching the midway point of their timeline (2015–2030) and still the need for further clarification remains essential to unlock the potential for promoting the sound planning and development of AD initiatives among organisational leaders, encompassing high-level policymakers, field managers, and private operators (Ampese et al., 2022). To the best of the authors' knowledge, a few studies, as listed in Table 1, have directly highlighted the contribution of AD to various aspects of SDGs. They indicated that these technologies could progress SDG 7 (affordable and clean renewable energy), SDG 11 (sustainable cities) and SDG 17 (partnership). However, none of these works has specifically targeted and demonstrated AD and its role in SDGs properly (Khan and Kabir, 2020; Ye *at al.,* 2023). Furthermore, some previous studies have focused on biogas production and its role in achieving specific SDGs, such as reducing the burden on natural energy resources (SDG 7) and addressing climate change concerns (SDG 13) (Obaideen et al., 2022; Welfle and Röder, 2022). Finally, WBA (2018) and Ampese et al. (2022) showed that AD is promising for improving circular economy processes and practices in several areas of industry.

Therefore, this study aims to address these unexplored aspects and provide a more comprehensive understanding of the contribution of AD to the achievement of each SDG. Specifically, this paper covers two areas: (1) an investigation into the contributions of AD technologies to each SDG and associated targets, and (2) a detailed discussion of how AD technologies can help achieve these goals at the municipal level. This understanding may allow policymakers, funders and investors to strategically allocate resources or facilitate collaboration with organisations, governments, and communities. Furthermore, the research findings are anticipated to benefit the academic community specialising in AD research topics, enabling them to consolidate ongoing or future research related to the connection between AD and SDGs which result in obtaining supports from both governmental bodies and private industries.

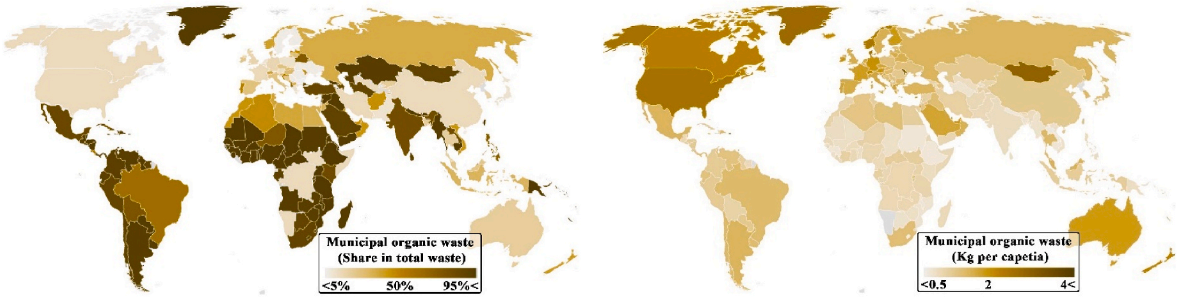
2. Research design and structure

The appropriate research works for this study were collected from the Scopus search engine following the guidelines suggested by Moher et al. (2009) and refined through a set of four search and screen strategies (S_1–S_4) as outlined in Table 2. The initial search results yielded 1348 publications in S_1, which were gradually narrowed down through the subsequent steps S_2–S_4. Based on the analysis of the collected papers in S_1 which focused on examining the sustainability of AD fed by municipal organic wastes, it was found that AD has been analysed based on various factors, including (1) input and waste resource types, (2) chemical processes, applied pre-treatment or co-technologies advances, and (4) outputs and side products, as illustrated in Fig. 2.

The primary waste resources used in AD include municipal wastes, such as sludge from water and wastewater treatment plants, municipal solid waste, garden or landscaping waste, agricultural and livestock wastes, such as feed residues, crops and harvest residuals, and manure, or industrial and solid non-hazardous wastes (Cudjoe et al., 2022). However, this study has limited its scope to only municipal organic waste due to its importance in achieving the SDGs, as discussed in the previous section. Furthermore, this study only includes published research works for the last decade (See S_2 strategy in Table 2), and many industrial reports are excluded from this study due to the inability to verify their claims, which are sometimes expressed as brand promises or commercial advertisements.

The AD process is a multi-step process consisting of a consortium of microbes which can be classified along with a series of metabolic pathways known to be both biological and chemical. These pathways include enzymatic hydrolysis, acidogenesis/fermentation, acetogenesis and methanogenesis (Patel et al., 2023). The enzymatic hydrolysis stage is a chemical process where, complex organic molecules are converted into a simple substance such as amino acid, long-chain carboxylic acid, and sugars (Rasapoor et al., 2020). Fermentation is a biological process in which bacteria are used to decompose the simple monomers to sugars and amino acids into different by-products such as ammonia, hydrogen, organic acids, and carbon (Dennehy et al., 2016). Similarly, acetogenesis is the biological reaction, where volatile fatty acid is converted into NH_2, H_2, and CO_2. Methanogenesis is another biological process where methanogens are used to convert digested materials into CH_4 and CO_2 (Cudjoe et al., 2022).

While impact of these processes can be investigated here, this study considered AD as a 'black box' technology, and mentioned chemical or detailed co-technological processes were excluded to focus more on a holistic but comprehensive understanding of the link between AD and the SDGs. To accomplish this goal, the S_3 screening strategy focuses on various sustainability dimensions, encompassing economic, social, and environmental aspects, which serve as the primary domain keywords for identifying pertinent research papers. Subsequently, the S_4 strategy is employed to identify papers explicitly discussing the role of advanced



(a) (b)

Fig. 1. Geographical distribution of generated municipal organic waste: (a) share of generated municipal organic waste in comparison to total generated waste (b) municipal organic waste generated per capita (Raw data is obtained from WBA (2023).

Table 1
Recent research works on role of municipal organic waste management technology to directly address contribution of AD to the SDGs[a].

Area of research	Highlighted SDG points	Reference
Potential assessment of waste-to-energy technologies	AD can help address SDG 7 by producing clean and renewable energy and SDG 11 by providing a sustainable solution for managing organic waste and reducing the burden on landfills.	AlQattan et al. (2018)
State of art for AD	Contribution of AD is expressed towards achieving all 17 SDGs.	World Biogas Association WBA (2018)
Economic benefits and cost prevention of using waste-to-energy technologies	Waste-to-energy technologies can contribute to achieving SDG 7 by providing clean and affordable energy through the conversion of waste into electricity, heat and fuel, and support SDG 11 by promoting sustainable cities and communities through the reduction of waste disposal in landfills and the recovery of valuable resources from waste.	Khan and Kabir (2020)
Circularity and sustainability indicators for measuring performance of AD	Identifying and measuring environmental, economic and social indicators are important criteria for assessing the sustainability of waste management systems such as AD in meeting SDG targets.	Mancini and Raggi (2021)
Household-based factors affecting biogas uptake	Biogas can significantly mitigate energy poverty and climate action to obtain the SDG 7 and SDG 13. It also can indirectly support SDG 8 by improving employment in rural areas, embrace innovative technologies resulting in SDG 9, and serve to support gender equality (SDG 5)	Ahmad and Wu (2022)
Bibliometric analysis of research works on AD	The production of bioenergy and biofuels from AD processes can be an alternative to meet the relevant SDGs.	Ampese et al. (2022)
Evaluation of bioenergy generation	Biogas generation directly contributes to 12 out of the 17 SDGs, mainly SDG 7, SDG 9, SDG 11 and SDG 13.	Obaideen et al. (2022)
Sustainability mapping of bioenergy generation	Bioenergy technologies are intrinsically linked to the SDGs more than other renewable sources and should be prioritised as the first choice for driving sustainable development.	Welfle and Röder (2022)

SDG 7: clean energy SDG 9: job creation SDG 11: waste management for sustainable cities/communities SDG 13: climate action.

[a] The search in the Scopus database covering the last decade (2013–2023) was based on keywords “Bioenergy”, “Biogas”, “Waste-to-energy”, “Anaerobic digestion”, “Sustainable development goals”, and “Sustainability”. Papers were reviewed then to select appropriated journal papers. Furthermore, relevant accredited reports were selected and reviewed to find the contribution of the aforementioned technologies in SDGs.

technologies in advancing SDGs.

As a result of the refined search, only 70 research works were found, and among them, only 8 journal papers specifically focused on different aspects of SDGs related to AD. This finding indicates that the existing scholarly literature on the direct relationship between AD and the SDGs is relatively scarce. While there might be a broader body of research on AD or the SDGs individually, the specific exploration of how AD aligns with and contributes to the achievement of the SDGs seems to be limited.

Table 2
Flowchart of the search strategies in the study.

Code	Search and screen strategy	Keywords	No. of papers
S_1	Finding publications examining the sustainability of AD fed by municipal organic wastes	TITLE-ABS-KEY (((Municipal AND Organic AND Solid) AND Waste) AND (Anaerobic AND Digestion) OR (Waste-to-energy) AND (Sustainable OR Sustainability) OR (Renewable AND Energy) OR (Biogas) OR (Bioenergy))	1348
S_2	The results were limited to the last decade, English language articles, and journal papers only with searching under titles, keywords, and abstracts.	AND PUBYEAR >2012 AND PUBYEAR <2024 (LIMIT-TO (DOCTYPE "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")) AND	720
S_3	The results were screened for sustainability assessment	(Economic OR Social OR Technological OR Technical OR Environmental) AND (Assessment) AND NOT to ((Chemical AND Process) OR (Polymer OR Protein OR Carbohydrate OR Fat OR Sugar OR ((Amino OR Fatty OR Volatile OR Acetic) AND Acid))	70
S_4	The results were screened for SDGs linkage	(Sustainable AND development) AND (Goals OR Indicators) OR (Poverty OR Hunger OR (Health OR Well-being) OR Education OR Gender OR (Clean AND (Water OR Sanitation) OR Energy) OR ((Economic OR Industry) AND Innovation) OR Inequality OR (City OR Communities) OR Consumption OR (Climate AND Action) OR (Life AND (water OR land)) OR Peace OR Justice OR Institutions OR Partnership	8

The fact that only 8 journal papers were identified suggests that further research is needed to investigate the connections between AD and the SDGs. The limited number of research papers also highlights the potential for additional research and exploration in this field. It signifies the importance of further investigating and understanding the role of AD in addressing the various dimensions of the SDGs. Such research can contribute to expanding knowledge, guiding policymaking and promoting the integration of AD into sustainable development strategies. Therefore, the selected papers are important because they are specifically dedicated to examining various aspects of the SDGs in the context of AD.

2.1. *Brief bibliometric analysis*

The study commenced by analysing on selected research publications to assess the global distribution of research on AD technologies in relation to the SDGs. Fig. 3a presents a visual representation of the findings, highlighting an interesting pattern. While AD technologies are under investigation worldwide, only a few countries appear to be actively aligning them with the SDGs. While the primary focus of the SDGs is to empower and uplift less developed nations, surprisingly, the analysis reveals that most prominent case studies are concentrated in economically advanced countries including the USA, UK, Italy, Germany, Sweden, India, and China. Among African countries, only a limited number of studies, primarily centred in Nigeria, have successfully established a connection between AD technologies and their contributions to the SDGs. In Asia, a similar trend emerges, with limited research in the Middle East, specifically in Iran, Turkey, and Pakistan,

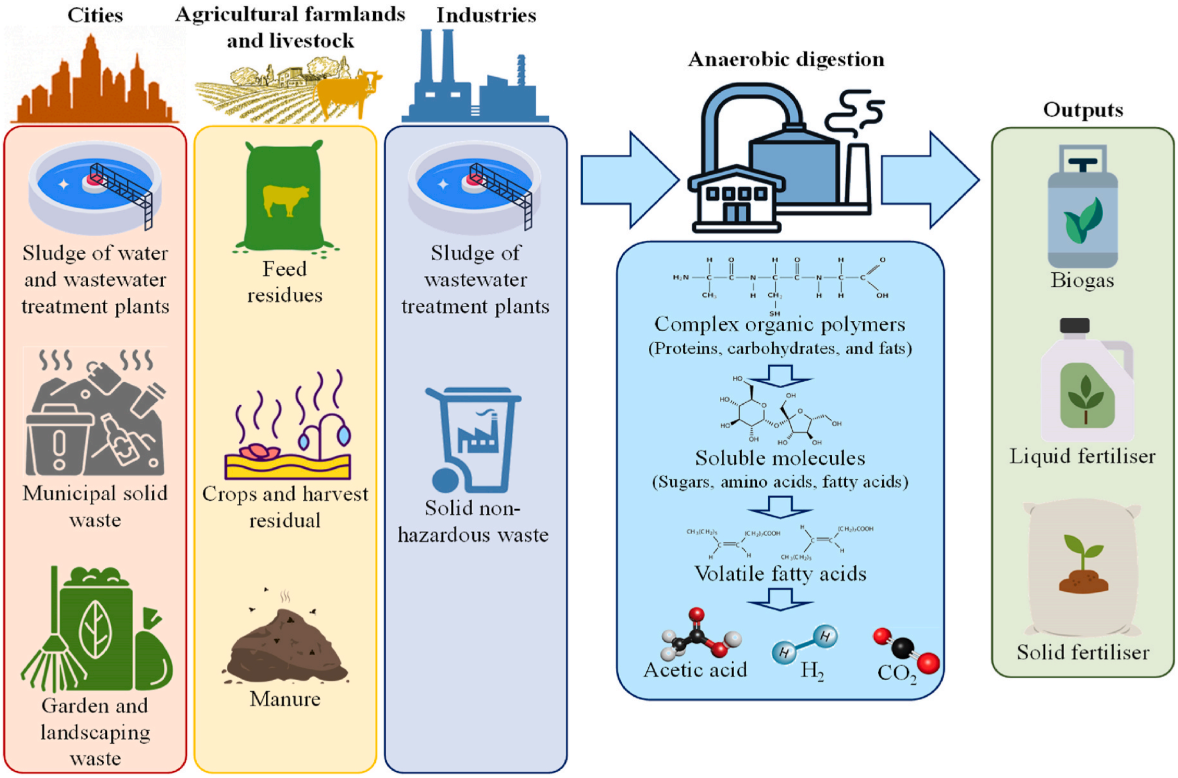


Fig. 2. Schematic illustration of various biorefinery inputs and outputs of AD processes.

addressing the SDGs' perspective. These findings highlight a gap in research distribution and suggest a significant opportunity for other countries, particularly developing countries to explore potential links between their AD studies and contributions to the SDGs.

The analysis also incorporated the application of VOS Viewer software, which was employed to delve into the bibliometric knowledge domain. This examination was based on the co-occurrence of words on keywords, titles, and abstracts, co-occurrence analysis and full counting method. Fig. 3b, derived from the content of the selected studies, reveals three prominent clusters. The red cluster concentrates on the technological and technical aspects of AD technologies, with a specific emphasis on enhancing processes for increased biogas production. In contrast, the blue cluster centres its attention on renewable energy sources such as biofuel, biowaste, and biomethane, with a focus on assessing profitability and greenhouse gas (GHG) emissions. Lastly, the green cluster encompasses research pertaining to specific environmental aspects, notably sustainability, circular economy and life cycle assessment (LCA). The interconnection between the red cluster and the two other clusters underscores the interdependence of technical aspects with broader sustainability and environmental considerations. This observation suggests that most research works are currently focused on aligning their technological enhancements with various aspects of SDGs, rather than placing the SDGs at the core of their research endeavours.

3. The potential contribution pathways of AD technologies to SDGs

The potential contribution of AD towards achieving the SDGs and the pathway for each contribution are explored in Fig. 4. In particular, AD can provide affordable organic fertilisers, which can help reduce poverty (SDG 1) and inequalities (SDG 10) by creating new local businesses and increasing crop yields, thus contributing to reducing hunger (SDG 2) (Giuliano et al., 2019). Both liquid and solid fertilisers can aid in restoring soils, nutrients and organic matter which is important for deforestation and nature restoration (SDG 15) (Tsapekos et al., 2021). The biogas/biomethane fuel produced can be used for cooking and off-grid local electricity or, at larger scale, in industrial, municipal and commercial settings. This can positively impact indoor air pollution (SDG 3), green energy production (SDG 7), and help in capturing GHG as climate action (SDG 13) (Carlos-Pinedo and Wang, 2022). Additionally, the emergence of many new green job vacancies in waste management, particularly in the collection of organic wastes, local electricity generation and green fertiliser trading, can promote economic growth (SDG 8) and reduce low-income inequalities (SDG 10) (Röder, 2016). These opportunities can also develop the natural efficiency of waste recycling processing i.e. harnessing the natural and normally uncontrolled process of biodegradation (SDG 12) and mutual industrial benefits by encouraging self-sufficient growth of micro-enterprises (SDG 9) (Sun et al., 2017).

In a social context, addressing educational inequalities (SDG 4) and gender equity (SDG 5) could be achieved effectively by providing reliable and locally generated electricity, particularly through small and micro-AD. Women and girls in households often bear the primary responsibility for collecting firewood, resulting in the loss of their time and opportunities, particularly for educational purposes (Vaneeckhaute et al., 2018). With the implementation of these new electricity resources, educational centres in poor areas can also receive the required energy they need. The development of micro-AD can therefore provide a significant source of income for low-income families, for whom child labour is often a necessity. However, when comparing it to solar energy in sunny equatorial regions, AD can be perceived as a costly and intricate method of electricity generation (Bywater et al., 2022). Nonetheless, when it comes to the utilisation of AD for cooking purposes in micro-scale systems, direct gas usage proves to be highly effective in eliminating the time and environmental challenges associated with the collection of firewood, primarily carried out by women (Lima et al., 2019). On a slightly larger scale, the production of off-grid biomethane offers another means to alleviate this burden. By employing upgrading equipment capable of producing as little as one m^3 of upgraded biomethane per hour, the biomethane can be compressed into gas bottles

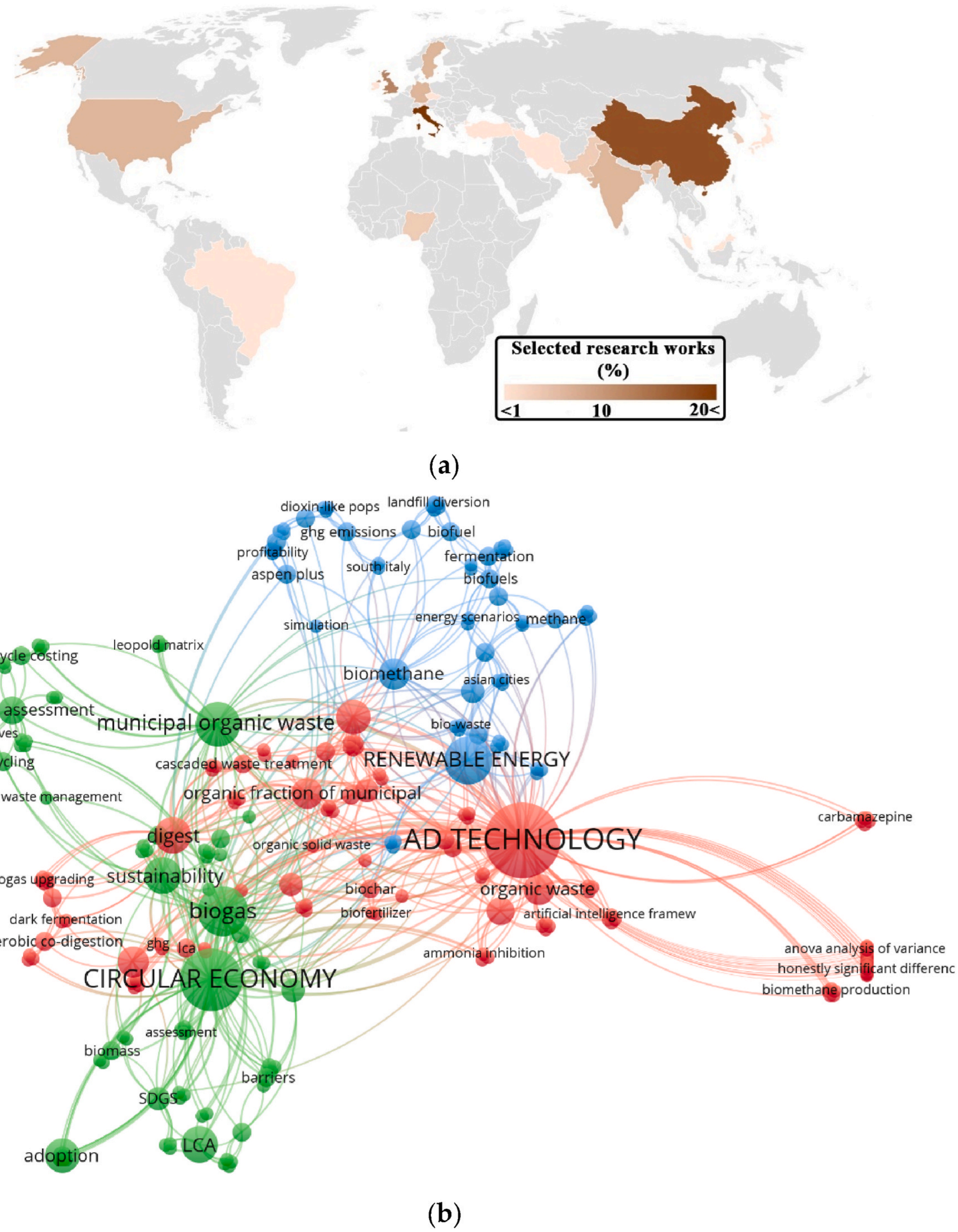


Fig. 3. Bibliometric analysis for the selected papers based on (a) geographical distribution, (b) cluster of keywords.

and used for cooking (Shaibur et al., 2021). This alternative, although more expensive, can be implemented centrally and at a larger scale, surpassing the capabilities of individual or small-scale biogas systems used for household cooking (Malet et al., 2023).

In addition, the implementation of AD can help prevent the discharge of waste leachate into surface and groundwater resources, thus reducing pollution in water bodies (SDG 6 and SDG 14). This technology, if deployed appropriately, can also help in reducing adverse impacts of other waste management technologies, for example, the soil/air pollution and large, often virgin, land area requirement used for landfill site (SDG 15) when implemented in near-natural ecosystems (Gao et al., 2021). In a larger-scale perspective, AD can prevent adverse environmental impacts of urban waste (SDG 12), such as air pollution, health risks, water pollution and land use change for waste management, whether implemented on a local or centralised scale (Dennehy et al., 2016). Moreover, anaerobic digestion can also aid in resolving international conflicts caused by GHG climatic issues or improper waste management (Adams and McManus, 2019), which helps to achieve SDG 16. The potential for constructive multinational collaboration, less complicated construction and easy access to develop AD systems can also provide mutual benefits for various parts of society, ultimately helping to meet the requirements of SDG 17 (Mancini and Raggi, 2021).

Each SDG is comprised of a set of specific targets to provide specific and measurable evaluation. While these targets are set for the country

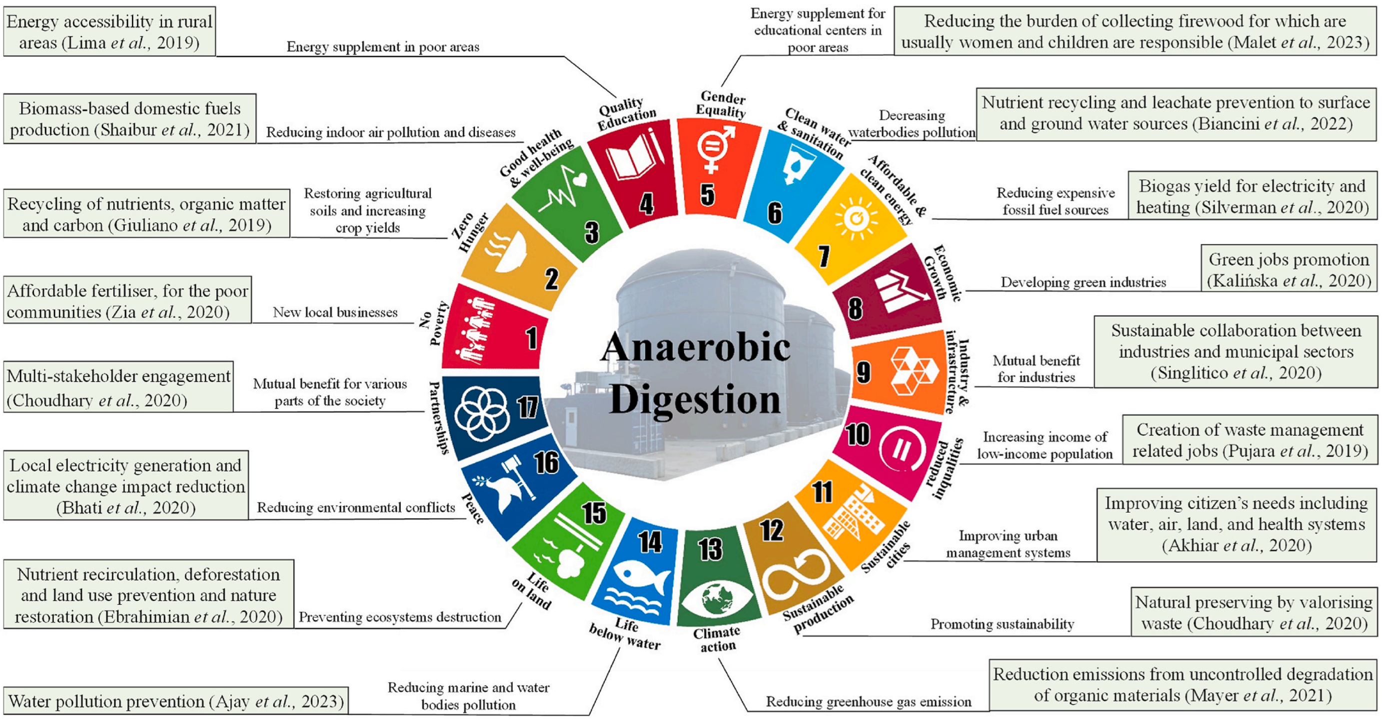


Fig. 4. Linkage between AD technologies and sustainable development goals.

scale, contribution of AD technologies can be numerate in this context. Therefore, to enable a more comprehensive analysis, AD inputs, such as the redirection of waste streams from landfills or open dumping to these systems, and outputs i.e. the production of solid/liquid fertiliser and yielded biogas can be linked to these targets. This linkage is portrayed in Fig. 5, which is rooted in original research but is inspired by selected papers cited in the reference section. This visual representation demonstrates how the fulfilment of SDGs can be supported by AD technologies. AD technologies can be associated with multiple targets, resulting in a complex network. A particular aspect of AD, whether it's an input or an output, can fulfil one or more targets simultaneously. Furthermore, these contributions can be categorised as either direct or indirect connections within this intricate network. Direct connections involve explicit efforts toward the achievement of a specific target or goal. In such cases, specific contributors are actively working to meet a particular objective. In contrast, indirect connections encompass scenarios in which contributors may not be directly involved in the attainment of a specific target. Instead, progress is supported through related mechanisms or intermediate activities. Essentially, the target is indirectly aided through contributions to other elements connected to it.

Using the organic portion of municipal organic waste in an AD system is mainly linked to the socially oriented aspects of the SDGs. This can increase equal access to basic services by preventing water and soil pollution caused by improper waste disposal into natural bodies, such as forests, rivers, aquifers and lakes (Chen et al., 2023a). It can also decrease the number of deaths and the number of people who are exposed or vulnerable to waste-related environmental shocks and disasters, particularly in slum areas. Such progress can aid in increasing sustainable urbanisation and capacity for participatory human settlement planning and management (Mayer et al., 2021). On an international scale, it can lead to the development and transfer of environmentally friendly AD to developing countries, which results in the reduction of local and international violence, wars and conflicts related to waste management, water pollution and climate change (Biancini et al., 2022).

Solid and liquid fertilisers mainly impact soils and agricultural activities (Yong et al., 2021). Using organic waste in this manner can provide sufficient and safe food for people in vulnerable areas and reduce extreme poverty by providing reliable fertiliser for developing local agricultural areas (Ardolino et al., 2021). Alternatively, soil pollution and fertiliser runoff into water bodies can be reduced by reducing/replacing traditional synthesized and chemical fertilisers with appropriately applied organic fertilisers (Yadav et al., 2022). Biogas generated by AD can be a sustainable solution for providing renewable energy, particularly for local poor areas, replacing unsafe home-based energy generation, e.g., from inefficient wood combustion in enclosed spaces (Temirbekova et al., 2021).

Finally, many new job vacancies in areas such as waste collection and treatment, green technological enterprises, local agricultural businesses, or industrial cooperation can be developed to increase high-value-added production and economic productivity, enhance global resource efficiency in the cycle of consumption and production, and define new scientific research and technological capabilities of related industrial sectors (Teimouri et al., 2019). It is expected that these new opportunities will mainly be expanded in low-income communities and developing countries. However, both transferring, or adoption of AD techniques may require the involvement of different organisational stakeholders (i.e. multinational corporations) whose culture or strategic drivers could enter into conflict with the affordances or potentialities of AD (Konti and Damigos, 2018).

4. Sustainability perspective of application of AD in SDGs

A more detailed analysis of the contribution of AD to sustainable development can be achieved by examining their impacts on each of the SDGs, classified into the sustainability pillars of economic, social and environmental aspects. Such an approach is recommended by the SRC (2017) which classifies each SDG into one of these three pillars. However, it should be noted that one SDG may be classified into more than one pillar based on the selected research works.

4.1. Economic perspectives

The contribution of AD in achieving the SDG targets from the

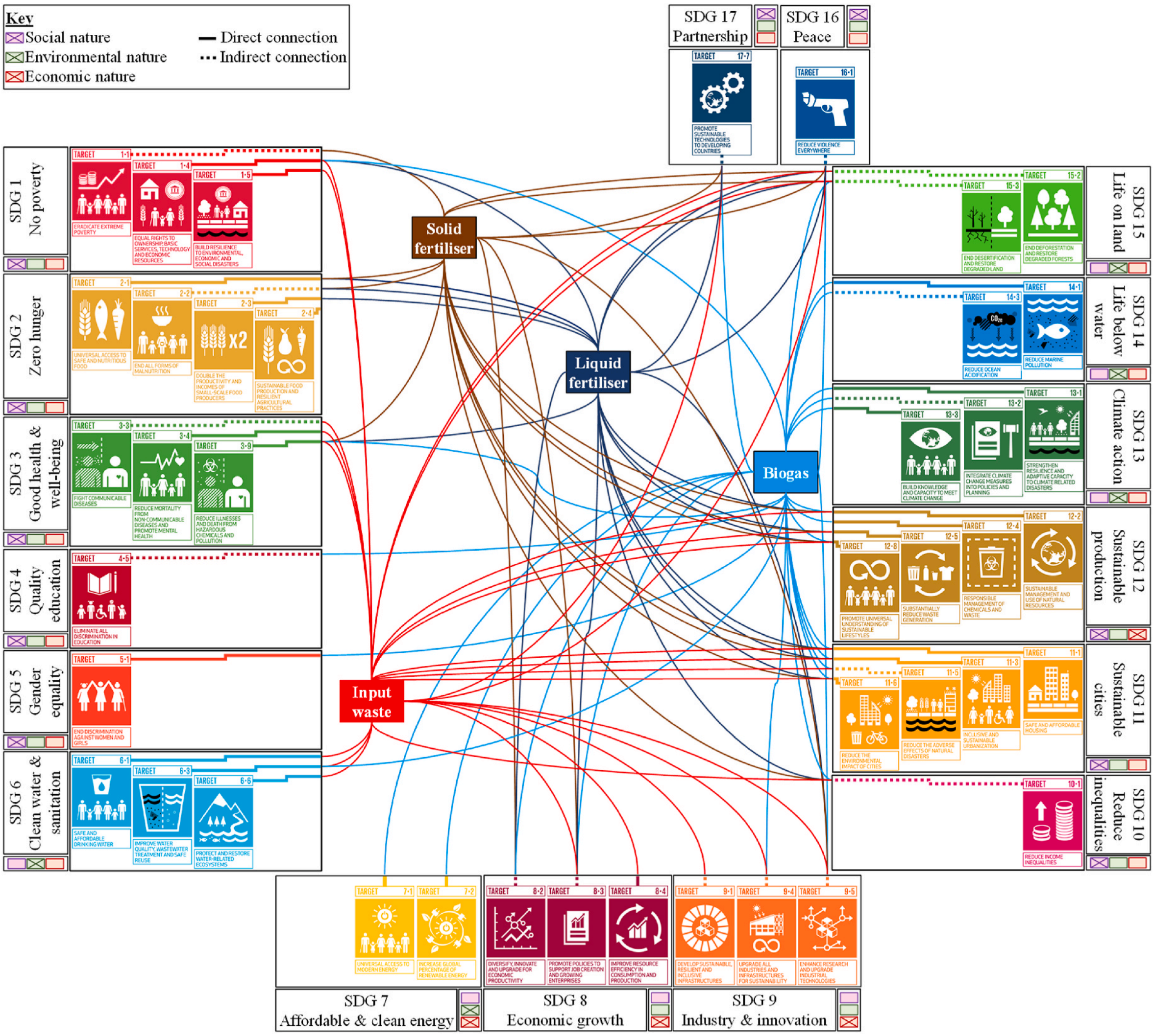


Fig. 5. Network connection between SDGs targets and input and outputs of the AD technologies.

economic perspective can be seen in Table 3. AD systems require human intervention at various stages, including waste collection, transportation, operation of AD facilities and management of by-products. Implementing AD projects can create job opportunities, particularly in waste collection and management sectors, providing income and livelihoods for individuals and communities affected by extreme poverty, helping them escape the cycle of poverty (Choudhary et al., 2020b). It was found that on average, for every 1000 tonnes of organic waste processed through AD, approximately 20 direct jobs were generated in waste collection and management sectors. Moreover, indirect employment effects, including supply chain and support services, resulted in a total of additional 15 jobs (Francini et al., 2019). These employment opportunities provided income and livelihoods for individuals and communities affected by extreme poverty, assisting them in breaking the cycle of poverty. In many developing regions, households lack access to clean and affordable energy sources. AD provides a decentralised renewable energy solution, allowing communities to meet their energy needs for cooking, heating, and lighting. AD systems are documented as potential of 30% reduction in energy poverty levels within the surveyed communities (112–135 million people) if all collected organic waste can be used and processed by AD (WBA, 2019). Access to reliable and sustainable energy not only improved living conditions but also had a transformative effect on livelihoods, education, health, and overall well-being (Barbera et al., 2022).

Adding value to waste through AD has also transformed it from a burden on the government into an opportunity to produce biogas and bio-fertiliser, and to create new jobs (Obaideen et al., 2022). For example, in the United States, biogas businesses created about 335,000 temporary construction jobs and 23,000 full-time operational positions, even though biogas represented less than 2.2% of total renewable energy in 2019 (American Biogas Council ABC, 2021). In China, biogas alone supported 209,000 workers in 2020, with the potential to create more jobs in the coming years (IRENA, 2021). Although the number of jobs created by AD may be lower than that of other renewable energy sources such as wind turbines and solar energy, it still represents a significant contribution. While AD has contributed towards the realisation of some SDGs from an economic perspective in certain regions of the world, its full implementation at the municipal level globally is still limited. AD is not yet in use in many parts of the world, highlighting the need for more research, investment and policy support to promote its adoption as a sustainable waste management and renewable energy solution (Yalcinkaya, 2020).

AD plays an essential role in sustainable waste management, which has far-reaching implications for poverty reduction. Poor waste management practices can have detrimental effects on human health, environmental quality and economic development, particularly in marginalized communities (Masala et al., 2022). By implementing AD, organic waste is appropriately handled, thereby reducing pollution and associated health risks. In addition, AD by-products such as digestate, can be utilised as a valuable resource for agriculture, promoting

Table 3
Connection between economic-based SDGs targets and AD.

SDG/Target	How AD supports the SDG targets	Reference
1.4: Basic services and economic resources	Increasing equal access to basic services by preventing water pollution, soil pollution and renewable energy	Yadav et al. (2022)
1.5: Environmental, economic and social disasters	Reducing exposure and vulnerability to waste-related environmental shocks and disasters	Smith et al. (2021)
7.1: Modern energy	Biogas as universal, sustainable and modern energy used for electricity, heating and fuel	Chiappero et al. (2022)
8.2: Economic productivity	Aiding in increasing high value-added production and economic productivity by providing renewable energy and fertiliser, potentially fostering innovative modern agricultural practices, e.g., hydroponic methods using liquid fertiliser	Yong et al. (2021)
8.3: Policies to support job creation and growing enterprises	Potentially creating new jobs and enterprises focusing on waste management collection systems, development and extending of AD systems and/or marketing of environmental-friendly AD outputs which result in track records to support associated green job policies	Francini et al. (2019)
8.4: Resource efficiency in consumption and production	Promoting global resource efficiency in the cycle of consumption and production through the mobilisation of circular economy principles	Barbera et al. (2022)
9.1: Sustainable, resilient and inclusive infrastructures	Developing quality, reliable, sustainable and resilient waste management infrastructure supporting human well-being	Mayer et al. (2020)
9.4: Industries and infrastructures for sustainability	Upgrading waste-related and energy production infrastructure through the deployment of this sustainable, clean and environmentally sound technology	Cudjoe et al. (2020)
9.5: Research and upgrade industrial technologies	Enhancing the scientific research and technological capability of related industrial sectors	Sanchez et al. (2017)
12.2: Sustainable management	Achieving the sustainable management and efficient use of natural resources by valorising organic wastes	Yalcinkaya (2020)
12.5: Waste generation	Substantially reduce waste generation by recycling and reuse	Lee et al. (2020)
12.8: Understanding of sustainable lifestyles	Helping to foster awareness about sustainable development and related technologies which are in harmony with nature, by installing and promoting local AD for communities	Masala et al. (2022)

sustainable farming practices and supporting food security (Silverman et al., 2020). AD can provide access to clean and affordable energy in areas where energy poverty is prevalent. By converting organic waste into biogas, AD systems can generate a renewable energy source that can be used for cooking, heating, lighting, and other energy needs, thereby enhancing the quality of life for communities by providing a reliable and sustainable energy solution (Sanchez et al., 2017). AD contributes to effective waste management, particularly in areas with limited waste infrastructure or inadequate waste management practices. AD systems can process various types of organic waste, such as agricultural residues, food waste and animal manure, and convert them into biogas and digestate. Proper waste management through AD helps reduce environmental pollution, improve sanitation and protect public health (Kalińska et al., 2020).

AD offers a sustainable waste valorisation approach that allows for the conversion of organic waste into valuable resources, such as biogas and digestate (Francini et al., 2019). By implementing AD systems, businesses and industries can reduce their waste disposal costs and generate revenue from the sale of biogas or digestate. This waste valorisation approach transforms waste materials into valuable commodities, leading to economic savings and improved resource efficiency (Mayer et al., 2020). By utilising biogas for on-site energy production, businesses can reduce their reliance on costly fossil fuels, resulting in significant energy cost savings over time. This contributes to increased resource efficiency by optimising energy consumption and minimising expenditure on non-renewable energy resources (Lee et al., 2020).

AD promotes a circular economy model where resources are utilised efficiently throughout the production and consumption cycle. Organic waste which would otherwise be discarded or incinerated, is instead transformed into valuable products. This reduces the need for extracting and processing virgin resources, resulting in cost savings and minimising the environmental impact associated with resource extraction and production (Cudjoe et al., 2020). The digestate produced during the AD process serves as a nutrient-rich organic fertiliser. By utilising digestate as an alternative to chemical fertilisers, farmers can reduce input costs and improve soil fertility. This enhances resource efficiency in agricultural production by minimising the reliance on expensive synthetic fertilisers and maximising the utilisation of organic waste resources (Yong et al., 2021).

4.2. *Environmental perspective*

Table 4 presents anaerobic digestion's major environmental contribution with regard to SDGs. Improper disposal of organic wastes can contaminate water bodies, including rivers and aquifers, compromising their quality and making the water unsafe for consumption. AD helps reduce this pollution of water sources. Digestate, a nutrient-rich by-product (Bajracharya et al., 2022) of AD, can be utilised as an organic fertiliser in agriculture. When used properly, digestate can reduce the reliance on chemical fertilisers, which can contribute to water pollution when applied improperly or in excess. In this regard, AD can help stabilise and recover nutrients, including phosphorus, in organic waste materials. During the digestion process, organic matter is broken down, and nutrients become incorporated into the digested material or biosolids. These biosolids can have reduced solubility and are less likely to release nutrients quickly when applied to soil, reducing the risk of nutrient leaching into water bodies, and reducing the need for synthetic fertilisers (Zhou et al., 2022). Therefore, AD supports sustainable agriculture practices, reduces nutrient runoff and safeguards water quality and play a role in the water-energy nexus, which refers to the interdependence of water and energy resources (Ardolino et al., 2021).

Properly managed AD systems also can help reduce the risk of eutrophication in water bodies. By stabilising and recovering nutrients from organic waste, AD can minimise nutrient runoff and leaching, which are common contributors to waterbody eutrophication (Bhandari et al., 2023). According to estimates, harnessing all the available organic waste through AD has the potential to replace significant amounts of essential nutrients in the form of organic fertiliser. This includes approximately 5.03 million metric tonnes of nitrogen, 0.75 million metric tonnes of phosphate, 1.8 million metric tonnes of potash, 1.1 million metric tonnes of calcium, 0.13 million metric tonnes of magnesium, and 0.58 million metric tonnes of sulphur. These nutrient reserves are substantial and could effectively fertilise approximately 53 million hectares of arable land (WBA, 2019).

Continuous efforts are being made to provide clean, renewable energy to more people globally, and where more organic waste is being diverted from landfill and converted into renewable energy through AD, the efficiency of natural resource usage is enhanced by minimising air and water pollution and improving the waste recycling process (Chen et al., 2023b). The increasing global application of the technology has

Table 4
Connection between environmental-based SDGs targets and AD.

SDG/Target	How AD supports the SDG targets	Reference
6.1: Safe and affordable drinking water	Enhancing safety and affordability of water resources by proper waste management and preventing associated water pollution	Bajracharya et al. (2022)
6.3: Water quality	Enhancing water quality, especially drinking water, by proper waste management and providing renewable energy for local treatment facilities	Ardolino et al. (2021)
6.6: Water-related ecosystems	Helping to protect areas such as forests, rivers, aquifers and lakes through using collected organic waste in AD	Biancini et al. (2022)
7.2: Renewable energy	Biogas as an increasing share of renewable energy generation in the global energy mix	Wang et al. (2022)
13.1: Resilience and adaptive capacity to climate related disasters	Strengthening resilience and adaptive capacity to global warming climate-related hazards by beneficially utilising the energy produced by organic biodegradation in AD and replacing the GHG emissions produced by fossil fuel-based energy resources	Chen et al. (2023b)
13.2: Climate change measures into policies and planning	Improving awareness-raising on climate change impact reduction by establishing local and community-based anaerobic digestion	Mayer et al. (2021)
13.3: Knowledge and capacity building to meet climate change	Helping to improve awareness of the contribution of AD at any scale in mitigating climate change, from small local, community-based installations through to large municipal-scale systems.	Srivastava et al. (2023)
14.1: Marine pollution	Reducing marine pollution generated by land-based activities such as open dumping, unsafe landfilling and ocean discharge of waste	Ajay et al. (2023)
14.3: Ocean acidification	Minimising the adverse ecological impacts of dumping of untreated organic wastes into oceans	Gadaleta et al. (2023)
15.2: Deforestation 15.3: Desertification	Biogas can replace wood as a local fuel, helping to minimise the deforestation associated with the over-harvesting of wood as an energy source. Optimising food production on existing agricultural land through the addition of vital nutrients and organic matter (carbon) contained in the AD fertiliser could help to reduce the forest clearance associated with farmers abandoning unproductive (desertified) soils in favour of virgin cleared soils. Recycling organics through AD could reduce land use associated with open dumping and unsafe landfilling of such materials.	Guillaume et al. (2023)

positive impacts on the environment, and this has been observed in various research works that show the contributions of AD towards climate change mitigation by minimising air pollution and environmental sanitation through water and soil pollution prevention in different parts of the world (Srivastava et al., 2023).

The implementation of AD in developing countries has had significant benefits in reducing the adverse effects of household energy sources such as wood, coal and liquefied petroleum gas on the environment (Zhang et al., 2020). Biogas (or biomethane) can be used for household cooking, heating and lighting, serving as a cleaner and more sustainable alternative (Bywater et al., 2022). AD also holds the potential to significantly reduce global greenhouse gas emissions. According to a report by the WBA in 2021, the application of AD in treating organic waste is expected to achieve a 10% reduction in emissions, and as of now, 2% of that target has already been met. Efforts are being made to increase the number of digesters, particularly in China and India, as part of renewable energy plans. Biogas derived from organic waste and agricultural by-products replaces fossil fuels and reduces carbon dioxide emissions, promoting decentralisation and democratisation of energy generation due to its simplicity and fewer geographical limitations (Obaideen et al., 2022).

AD provides an effective solution for managing organic waste, reducing the need for unsustainable waste disposal methods such as open burning or landfilling. Properly managing organic waste through AD reduces pressure on natural resources, including forests and agricultural lands (Shah et al., 2021). By substituting traditional biomass with biogas, AD helps prevent deforestation for fuel wood and mitigates the associated environmental degradation. AD systems can be integrated with land restoration and rehabilitation efforts (Rotthong et al., 2023). For instance, degraded or marginal lands can be used for cultivating energy crops or establishing dedicated AD facilities. By reclaiming and revitalizing these lands through AD, it helps prevent further deforestation or desertification by focusing on areas already impacted by or unsuitable for traditional agriculture (Demichelis et al., 2022). Finally, AD contributes to the reduction of greenhouse gas emissions, particularly methane, a potent greenhouse gas. By capturing and utilising methane produced during AD, it prevents its uncontrolled release into the atmosphere. This helps mitigate climate change impacts, which can indirectly contribute to deforestation and desertification by preserving stable climate conditions that support healthy ecosystems (Llano et al., 2021).

4.3. *Social perspective*

The global increase in biogas generation is a positive development that indicates continuous efforts are being made to improve living standards by providing better air quality and better health as listed in Table 5. Cooking with biogas replaces the use of firewood, which produces harmful smoke and soot particles that can negatively impact human health (Malet et al., 2023). For example, a study of AD for 12 remote families in a project to replace firewood with biogas showed that firewood use was reduced by 50–60%, and cooking time was reduced by 1 h (Lima et al., 2019). To extend this, it is estimated the AD facilities can generate 500 direct jobs in medium size cities, 100 job in rural areas, and lifting up to 200 families out of extreme poverty in a poverty-stricken community (WBA, 2021). This resulted in a reduction in the burning of fossil fuels and deforestation, which contribute immensely to global warming, climate change and melting of the polar ice, all of which have adverse effects on human health. The use of biogas also helped to reduce the burden on women in these remote families who are often responsible for collecting firewood for cooking (World Biogas Association WBA, 2018). Other studies have also revealed that the use of biogas instead of biomass in homes in India and Bangladesh helped to reduce the residents' exposure to a few short-lived climate pollutants and black carbon that can interrupt monsoons and accelerate glacier melting, threatening water and food security (Pujara et al., 2019).

The increasing application of AD for biogas generation has contributed to improving the quality of education in rural communities by increasing energy accessibility. (Shaibur et al., 2021). It also improved the cooking environment for biogas digesters, which decreased the time required to collect wood for cooking food, providing people with more time to devote to education. Similarly, the commissioning of 4475 micro

Table 5
Connection between social-based SDGs targets and AD.

SDG/Target	How AD supports the SDG targets	Reference
1.1: Extreme poverty	Eradicate extreme poverty through job creation in waste collection and management, and through the provision of soil organic matter and locally-produced non-fossil fuel derived fertiliser for agriculture	Sadhukhan and Martinez-Hernandez (2017)
2.1: Safe and nutritious food	Providing sufficient and safe food for people in vulnerable areas by providing nutrients for local food growing	Ayodele et al. (2017)
2.2: Malnutrition	Providing nutrients through developing local agriculture based on liquid and solid fertiliser obtained through AD	Lombardelli et al. (2017)
2.3: Productivity and incomes	Increasing agricultural productivity in agricultural food production by providing organic fertiliser	Giuliano et al. (2019)
2.4: Sustainable and resilience production	Maintaining ecosystems and improving land and soil quality through the responsible use of organic and environmentally friendly liquid and solid fertiliser	Ayodele et al. (2018)
3.3: Communicable diseases	Reducing associated communicable diseases, especially water-borne diseases by preventing water resource pollution from the uncontrolled biodegradation of organic wastes	Falahi and Avami (2020)
3.4: Non-communicable diseases	Reducing premature mortality from non-communicable diseases which arise from improper waste collection and management	Shaibur et al. (2021)
3.9: Illnesses and death from hazardous chemicals and pollution	Reducing the number of deaths and illness from hazardous soil, air and water contaminants by safely collecting waste and replacing unsafe home-based energy generation (e.g. wood) with reliable locally produced energy	Obaideen et al. (2022)
4.5: All discrimination in education	Aiding children to complete their education by setting them free from providing time-consuming energy resource collection	Lima et al. (2019)
5.1: Discrimination against women and girls	Decreasing discrimination against girls and women providing time consuming home-based energy resource collection (i.e. wood)	Malet et al. (2023)
10.1: Income inequalities	Helping to create and sustain waste management-related local jobs for low-income populations	Pujara et al. (2019)
11.1: Safe and affordable housing	Providing adequate, safe and affordable basic services and upgraded slums by improving waste collection, removing associated waste pollution and the creation of related green jobs	Afifi Akhiar et al. (2020)
11.3: Inclusive and sustainable urbanisation	Aiding sustainable urbanisation and improving the capacity for participatory human settlement planning and management, especially by establishing local scale technologies	Maria et al. (2016)
11.5: Natural disasters	Helping to reduce the number of deaths and the number of people affected by waste-related disasters with a focus on protecting the poor and people in vulnerable situations	Teimouri et al. (2019)
11.6: Environmental impact of cities	Improved waste management, particularly of organic wastes, reduces the emissions associated with uncontrolled biodegradation, thus improving air quality in cities. Recycling nutrients to farmland further decreases the environmental impact of these urban areas. Renewable electricity production, biomethane used to replace fossil-derived natural gas in vehicles and biogas to replace wood also improves urban/peri-urban environmental impact.	Sohoo et al. (2021)
12.4: Chemicals and waste	Improving environmental management of organic wastes throughout their life cycle significantly reduces emissions to air, water and soil, minimising their adverse impacts on human health and the environment	Gómez-Camacho et al. (2021)
16.1: Violence everywhere	Reducing local and international violence, wars and conflicts related to waste management, water pollution and climate change	Bhati (2020)
17.7: Sustainable technologies to developing countries	Developing and transferring robust and appropriate AD to developing countries	Choudhary et al. (2020)

digesters in India in 2015 for biogas production used in homes for cooking and heating hot water helped to improve the quality of education of children within the community. This was because the women had more time to devote to the education of their children (World Biogas Association WBA, 2018).

In addition to its impact on the environment and public health, the increasing application of AD has also demonstrated its potential to contribute towards achieving SDGs related to sustainable cities and communities, such as diverting organic waste from landfills which indirectly has health benefits. Several countries, including China, India, USA, France, Italy, UK and Germany have constructed digesters to treat various organic wastes, thereby improving the hygiene of the environment and protecting it from disease vectors and spread of infectious pathologies by the improper management of landfills (Sohoo et al., 2021).

Finally, AD technologies can contribute to local, regional, and global peace i.e., reducing conflicts and tensions indirectly through several mechanisms: (1) they can also contribute to more sustainable agriculture and improving food security which resulted in reducing the risk of conflicts driven by competition for resources (Giuliano et al., 2019); (2) the job creation potential, particularly in rural or marginalized areas, can contribute to economic stability. When people have access to employment opportunities and livelihoods, it can mitigate the conditions that sometimes lead to social unrest and conflicts (Vides-Prado et al., 2023); (3) promoting resource efficiency can reduce the environmental stressors on land and water resources, which are often sources of contention and conflict, especially in regions with limited access to these resources (Bhati, 2020); (4) AD can also provide a decentralised renewable energy solution in areas where access to reliable and affordable energy is limited and consequently enhance the quality of life, reduce energy-related conflicts, and improve social well-being (Gibellato et al., 2023); (5) collaborative efforts to implement AD projects that address shared environmental challenges can foster cooperation and diplomacy between neighbouring regions or countries. Joint initiatives to manage waste, reduce pollution, and generate clean energy can serve as a basis for peaceful relations. Furthermore, involving local communities, and community engagement can promote social cohesion and reduce internal conflicts and would be an opportunity for developing digital visualisation technologies for monitoring and managing solid waste systems (Bakhtiari et al., 2023a).

5. Sustainability challenges and recommendation for AD applications

The successful implementation of AD for managing organic wastes is often hindered by challenging factors that may prevent the full realisation of the SDGs. These challenges, as illustrated in Fig. 6, is classified into four categories of technological, social, economic, and environmental factors. Although these categories could be regarded as isolated from each other, in this review paper, the **systemic connections** are acknowledged between them which should also be considered when recommending strategies to achieve the effective implementation and utilisation of AD as a creative innovation (Córdoba-Pachón, 2018; Midgley and Lindhult, 2021).

5.1. Technological factors

Infrastructure access is one of the most crucial technological challenges for developing AD (Nevzorova and Kutcherov, 2019). In developed countries, infrastructure problems affect the transport sector e.g., limited access to vehicle refuelling stations hampers the widespread use of biomethane vehicles, thereby creating a barrier for biogas as a feasible fuel for vehicles (Amuzu-Sefordzi et al., 2018). Furthermore, poor waste collection, improper waste source segregation, inadequate waste transportation and physical space allocation increase the risk of supply chain disruption, creating a barrier for the utilisation of waste in biogas production (Mittal et al., 2018). However, due to long or difficult transportation routes, the collection of substrates, construction materials and deployment of digestate are challenging in rural and remote areas (Einarsson and Persson, 2017).

The availability of waste resources in sufficient quantities to sustain adequate biogas production can be a significant challenge in many communities (Clemens et al., 2018). This limits the amount of energy that can be generated from biogas digesters, leaving communities with no choice but to rely on alternative energy sources such as firewood, dung, and charcoal, as is common in many parts of Africa, or to abandon the use of biogas technology altogether (Quek et al., 2018). Additionally, the composition of the waste used for biogas production can also pose a challenge (Offie et al., 2022). The amount of biogas produced is highly dependent on the composition of the input waste and remains a critical factor for its utilisation. In cases where municipal organic waste does not have a consistent pattern of generation, the composition of biogas produced can be impacted (Offie et al., 2023).

The successful operation of biogas plants depends heavily on the experience and skills of the personnel operating them. Limited availability of technical staff can pose a significant challenge for the adoption of biogas technologies, as the number of qualified specialists, construction businesses, and technologists in biogas plants are relatively low (Amuzu-Sefordzi et al., 2018). Inadequate knowledge of the responsible agronomic use and fertilising value of digestate can also hinder successful deployment of AD (Uddin et al., 2016).

5.2. Social factors

The social challenges that hinder the implementation of AD are numerous and complex. One of the main challenges is the lack of social awareness and acceptance of the importance of waste segregation and associated sustainability actions. People often prefer easier and cheaper alternatives, making it difficult for the AD sector to receive significant attention in policy debates, especially in developing countries (Chen et al., 2017). This lack of attention may be due to a lack of educational and guidance materials for selecting and evaluating the economic feasibility of biogas technology, which can lead to low awareness and knowledge levels (Herbes et al., 2018). Stigmatisation can also have a negative impact on the sustainable dissemination of AD, as some local populations cannot accept the use of biogas due to traditional beliefs. These challenges have led to the failure of some AD projects because they are incompatible with local beliefs.

These institutional challenges, as part of social perspective, can have a significant impact on the scalability and sustainability of AD projects. Without government support, it may be challenging to secure financing, access subsidies, or obtain permits required for construction and operation (Msibi and Kornelius, 2017). As with other types of sustainability projects, the lack of an incomplete network of stakeholders and the highly centralised and hierarchical nature of programmes hinders contributions from the private sector (Piadeh et al., 2022; Bakhtiari et al., 2023b). Additionally, the presence of a high number of formal requirements, bureaucratic obstacles, and complex administrative and legal procedures can create difficulties, slowing down the process of

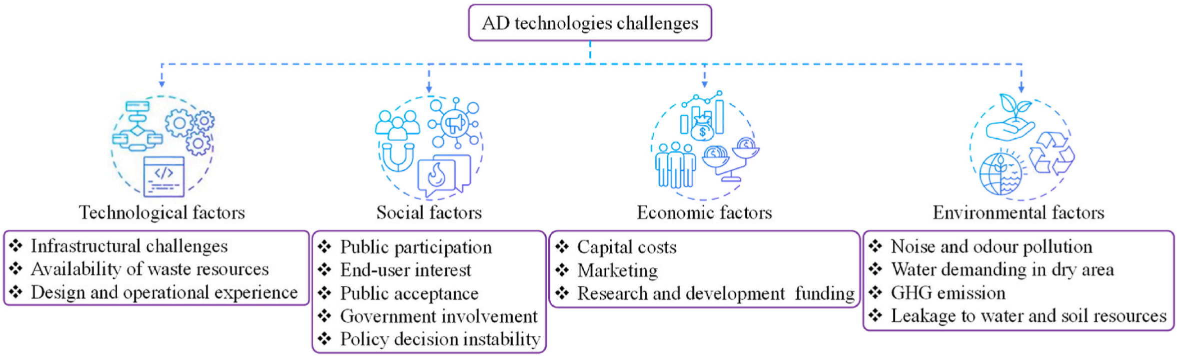


Fig. 6. Integration of main challenging factors affecting the AD applications.

installing AD plants (Chen and Liu, 2017). Insufficient information about the development of energy policy or the lack of private sector participation and poor coordination between the public and private sectors can also act as significant barriers to investment in biogas plants (Sanches-pereira et al., 2015). Furthermore, government strategies such as cancelling tax exemptions for biomethane can negatively impact the wider adoption of AD and slow down the growth of these technologies (Nevzorova and Kutcherov, 2019).

5.3. Economic factors

The AD is a capital-intensive process, with high upfront expenses for construction costs, equipment procurement, land allocation and, where implemented, biogas upgrading systems (Chen and Liu, 2017). While municipal organic waste is often free, its treatment and transportation costs can be significant, especially over long distances, negatively affecting the economics of AD (Mittal et al., 2018). This can make AD projects less attractive to investors, particularly if there is a lack of subsidies, financial support programmes or soft loans (Francini et al., 2019). To overcome these economic barriers, policymakers may need to explore new financing mechanisms to incentivise investment in ADs, including public-private partnerships, loan guarantees and tax credits. Governments could also provide direct financial support or offer other incentives to encourage private investment in AD projects. Such measures could help make AD systems more financially viable, while also contributing to more sustainable waste management practices.

AD faces several market challenges that hinder its widespread adoption. One of the major concerns is the lower prices of fossil fuels like natural gas in comparison to biogas, which reduces the economic viability of an AD system (European Commission, 2021). Another challenge is the difficulty in competing with existing soil and organic fertiliser manufacturers (particularly peat-based composts) for retailers and garden centres, as these suppliers prefer those who can offer a range of products and large quantities (Dahlin et al., 2015). These market barriers can result in a lack of active participation from biogas plant developers and hinder the growth of AD.

Another important barrier to the development of AD is the lack of research and development funding in developing countries. Inadequate financial budgets, a shortage of suitably qualified researchers and a lack of focus on sustainability planning are common problems in these countries (Nevzorova and Kutcherov, 2019). In addition, both academic and management sectors are often not well-informed about AD (Massaro et al., 2015). As a result, the adoption and application of these technologies are often overlooked in developing countries, further hindering the growth of the AD industry in those regions.

5.4. Environmental factors

Despite the significant potential for AD, there are some environmental challenges that potentially may need to be addressed. Increased vehicular movements and undesirable odours are some of the issues associated with some AD plants, particularly as the scale increases. Additionally, for some digester designs, a high demand for water resources can be a significant challenge (Mittal et al., 2018). In some instances, a proportion equivalent to nearly three times the amount of water and dry waste loaded into the digester is required, which can be problematic in regions with limited water availability, especially during summer (Offie et al., 2023). Moreover, operational faults such as broken digester seals, non-airtight gas valves, or leaking storage tanks can cause environmental problems such as increased GHG emissions, and ground/surface water contamination, as well as soil pollution (Li et al., 2018).

5.5. Recommendations

Although application of artificial intelligence and using machine learning models is out of scope of the present study, it could be incorporated into AD to monitor and improve their efficiency (Offie et al., 2022). This could help to increase biogas yield, enhance quality of solid and liquid fertilisers, improve the economics of the process and potentially overcome many of the sustainability problems previously mentioned (Offie et al., 2023). However, the use of remote sensing and automated systems is still challenging, particularly for poor and low-income areas; such challenges could be addressed through international support and collaboration in line with SDG 17. Furthermore, this study primarily focuses on extracting relevant aspects from sustainable-based research works, rather than explicitly examining the contribution of ADs in achieving the SDGs due to lack of sufficient materials. Furthermore, this research is mainly based on qualitative assessments and surveys of the selected research works, and quantitative analysis of the contribution of AD in SDGs is excluded due to difficulties in generalising the informative data typically reported in research works. However, it is recommended that future research directions include quantitative analysis to strengthen the findings of this study.

6. Conclusions

The contribution of AD to the SDGs has been analysed and reviewed in this paper that unveiled a multitude of connections and potential benefits across various aspects of sustainability, including social, economic, and environmental dimensions. More specifically, AD emerges as a tool that can directly or indirectly address a wide array of sustainability concerns, especially its role in pollution prevention, its positive impacts on health and well-being, potential to advance quality education, promoting gender equality and reducing inequalities for vulnerable groups in developing and low-income countries. Furthermore, the AD outputs e.g., liquid and solid fertilisers can play a significant role in enhancing agricultural productivity, curbing land-use changes, and generating new incomes in disadvantaged regions. In addition, there is a need to promote and expand the use of AD as a tool for sustainable development worldwide, shedding light on its often hidden but substantial contributions to achieving the SDGs.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used ChatGPT to improve readability and language of the text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing 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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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