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Biogas role in achievement of the sustainable development goals: Evaluation, Challenges, and Guidelines

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ABSTRACT

Background: Biogas is one of the promising renewable energy sources that successfully implemented at domestic and industrial scales. This work presents a preliminary evaluation of the role and contribution of biogas as a sustainable energy source towards achieving the sustainable development goals (SDGs).
Methods: This work summarizes the common feedstock and impurities in the biogas as well as the advantages and disadvantages of biogas compared with fossil fuels. Challenges and barriers associated with biogas production in developing and developed countries were elaborated and connected with SDGs. Finally, the relation between the circular economy, biogas, and related SDGs was presented.
Significant findings: The biogas has been found to have direct impacts and contributions to 12 out of the 17 SDGs. The main contributions of the biogas come from its ability to increase renewable energy, reduce climate change, enhance the waste management process, and create jobs. A set of 58 indicators was provided as a guideline for the stakeholders within the biogas industry to extend the benefits of the biogas toward the achievement of the SDGs and minimize any possible trade-off. The results of this work will help the different players within the biogas industry to form policy to ensure that biogas contribution to the SDGs is maximized.

1. Introduction

The world faces unprecedented human development and growth and expands human activities to all the environmental elements. However, natural resources and human activities must act responsibly and sustainably to preserve nature and human life. The world has seen remarkable landmarks of international policy shaping the natural environment, specifically, the Paris Agreement on Climate Change PACC and the 2030 Agenda for Sustainable Development [1,2]. The latter has specified seventeen sustainable development goals (SDGs) as a shared platform and a blueprint for peace and prosperity for humankind and planet Earth.

The rapid population growth and industrial progress have resulted in the accumulation of greenhouse gases (GHGs) in the atmosphere, thus the associated climate change [3,4]. As per the 1.5 °C Global Warming Special Study of the Intergovernmental Panel on Climate Change (IPCC), the planet has to restrict the increase in temperatures to 1.5 °C to prevent harmful impacts on habitats and communities. This target is still possible, but it means achieving net-zero global emissions by 2050 and implies immediate, solid, and long-term international climate action [5]. One hundred ninety-five nations agreed upon the PACC in 2015, and the COP24 rulebook implemented at the beginning of 2019 was the first move for a global energy change [6,7]. There is a need to quickly transform fossil energy into clean, sustainable, and renewable energy resources to control climate change [8–10]. Over many decades of study and industrial actions, today's common opinion is that incorporating waste-to-energy (WtE) is a viable choice for waste management, as it delivers various benefits [11–14]. WtE may be considered a semi-renewable energy source and a substitute for fossil fuels in several

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applications [15]. WtE systems are any technique that produces any energy, i.e., fire, power, or fuels, from a waste feedstock [16].

Agricultural waste, dairy waste, and municipal solid wastes are primary feedstock in bioenergy generation. Biogas is produced due to digestion, i.e., breaking down of organic waste, and is primarily composed of methane CH_4 and carbon dioxide CO_2 [17,18]. The feedstock needed for biogas production is expected, hence making them suitable in many countries globally. Municipal waste undergoes biological dissociation naturally, leading to the production of biogas. The biogas released can become an alternative energy source to support remote communities off the grid in some parts of the world, and it is also ideal for grid decentralization [19]. Other merits of biogas include: ensuring a decline in air and water pollutants, protection of vegetation, and environmentally friendly energy sources. Biogas further ensures the effective and beneficial management of municipal wastes [20,21]. In developed countries today, most biogas production systems are all automated with sophisticated sensors to monitor both electricity and CH_4 production [22]. Over 61 billion m^3 of biogas produced annually is shared between the United States, USA, Europe, EU, and Asia, with 14, 54, and 31%, respectively [23–26]. Recently, biogas was effectively used to directly produce electricity using fuel cells [27,28] that are considered one of the most effective energy conversion devices with low environmental impacts [29,30]. The capacity of the biogas is significantly increased in the last decade. Fig. 1 shows the power generated from biogas in terms of total capacity (TWh), including pumped energy storage and total generating capacity (GW).

Few works have been done to link the contribution of biogas to different SDGs. For instance, Lohani et al. [32] reported that small-scale biogas systems would contribute to SDG 1, SDG 3, SDG 5, SDG 7, SDG 13, and SDG 15. Similar conclusions were reported by Shaibur et al. [33] and Rosenthal et al., [34]. In another work, Rahman et al. [35] concluded that implementing biogas will help realize SDG 3, SDG 4, SDG 5, and SDG 7. Recently, Orner et al. [36] reported that agriculture residues' biogas contributes positively to SDG 6. As can be noticed from these studies and others [37–39], most of the studies did not provide a clear linkage between biogas and the SDGs. This manuscript covers a detailed explanation of these works and others in Section 6 (Contributions to knowledge). Most of the previous studies, focused on improving biogas technology and linking biogas to a specific SDG. Moreover, most of the earlier studies didn’t propose a method or guideline to enhance the contribution to the SDGs. Therefore, this work aims to analyze biogas's contribution into all the related SDGs and propose a set of indicators to improve the contribution of the biogas in acheiving the different SDGs. This analysis has several benefits for the different stakeholders. For instance, this analysis can help drive growth, address risk, attract capital, and form the appropriate policy in the biogas industry. This ultimately will assist in realizing SDGs.

Fig. 1. Total biogas energy (top) installed capacity in GW, (bottom) generation capacity in TWh. Data was obtained from IRENA [31].

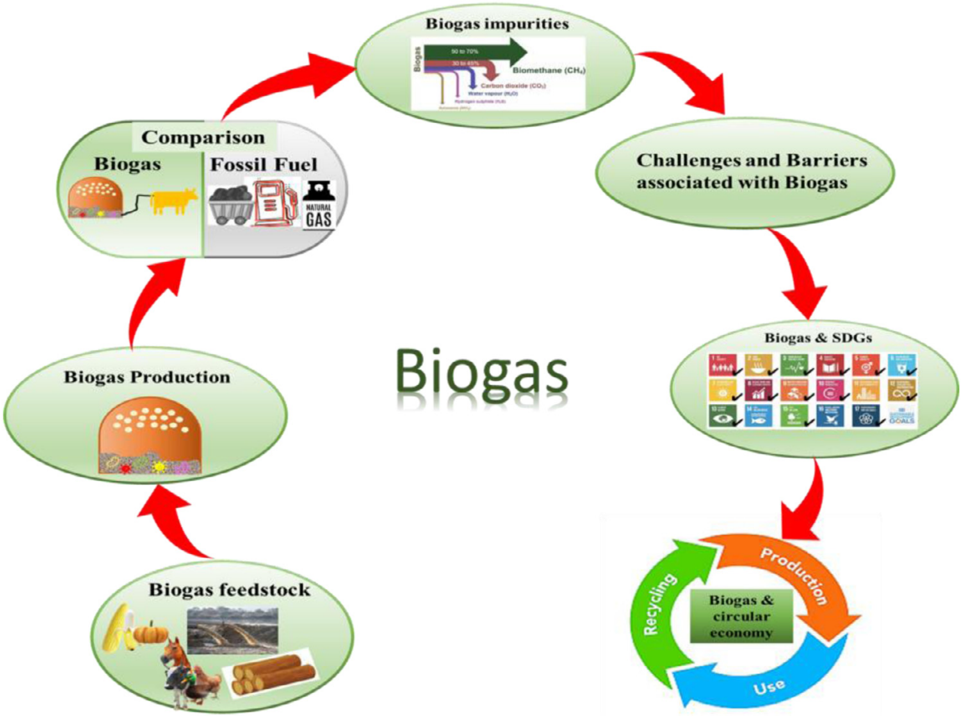

Fig. 2. Scheme of the main points covered in this study.

This work started with providing brief background about the biogas, feedstock of biogas production, biogas impurities, challenges associated with biogas production. Then the work summarises the current literature in the area of biogas and its role in the SDGs. After that, the work presents the challenges and barriers associated with biogas production with the related SDGs in developing and developed countries. Then the work presents an evaluation of the contribution of the biogas as a sustainable energy source towards the achievement of the different SDGs by using the qualitative assessment. Based on all the previous, the work proposes a set of indicators (58) to help the decision- and policy-makers in measuring the contribution of the biogas in the achievement of the different SDGs and reducing its impacts. In addition, the relation between biogas, circular economy, and SDGs was demonstrated. Finally, this work ends with the challenges, recommendations, and conclusion. Fig. 2 shows a scheme of the main points covered in this manuscript.

2. Biogas

Anaerobic digestion (AD) is a process in which microbes break down or digest complex organic material under anaerobic conditions to smaller molecules, including gaseous components, i.e., biogas that can be used as fuel for different purposes. This can be implemented at both micro-scale and macro-scale (for cities). Biodegradable wastes can be derived from a multitude of human, social and economic activities. This includes: food processing waste, agricultural wastes, food waste, and sewage sludge from wastewater treatment. The EU is the leading producer of electricity harnessed from biogas, where a total number of biogas plants over 18,200 with 12.6 GW power capacity installed in 2018, representing about 68% of the global capacity [40].

2.1. Feedstock for biogas production

The feedstock for biogas comes in solid or slurry states and sometimes concentrated. Common feedstocks utilized in biogas production are agricultural residues, food processing waste, municipal solid waste, and so forth. A summary of the biogas productivity coupled with CH_4 produced from various substrates is presented in Table 1 [41–44]. As being clear from the table, the CH_4 content is 51–65%, according to the substrate. The volume of biogas produced tends to increase upto200 m^3/tonne when the feedstock used is fresh.

Table 1
Biogas yield and methane content for different feedstock [41–44].

Substrate	Biogas yield (Vol./Wt.,%)	Methane, Vol.%
Distillers grains	40	61
Silage	200	50
Manure from pigs	60	60
Manure from cattle	40	60
Sorghum	108	54
Poultry manure	80	60
Cattle slurry	200	12.8
Beet	88	50
Organic waste	100	60
Whey	300	12

2.2. Biogas production

The production of biogas involves several stages with varying environmental impacts. The characteristics of the feedstock used and the design process, are what determine the composition of the biogas. The common method for biogas production is anaerobic digestion (AD), in which biological materials are broken down anaerobically [45]. The conversion stages in the breakdown of the biological materials include hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The initial stage of the process requires a robust storage medium, especially if the substrate does not undergo AD directly [46]. This is predominantly common when the agricultural feedstock is utilized as substrates. Similarly, to maximize the potential of CH_4 production from the substrate, various pretreatment techniques can be adopted, ranging from mechanical, thermal, and chemical paired with biological [46]. It is important to note that pre-treatment methods will vary subject to the type of feedstock being utilized.

The co-digestion stages ensure cheaper feedstocks are utilized in the process and support the addition of water and nutrients to some feedstock [47]. To curb these complex issues, monitoring the entire process is necessary to prevent operational challenges and establish a means of recovering CH_4 from the various substrates utilized [48]. To make the system robust, additives can be added to enhance AD performance [49]. To prevent the CH_4 gas from escaping, it is necessary to constantly check gas leakage from the digester, which is critical in improving the system's efficiency [50–52].

Biogas has several advantages such as:

- Renewable energy source: biogasis obtained from biomass that is available in the wastewater, agriculture residues, or municipal solid wastes [53].
- Pollution prevention: the production of biogas from various wastes will decrease soil and water pollution, reduce the amount of wastes transferred to landfills, and thus save money and underground water.
- Securing jobs: it is reported that biogas business has created around 335,000 temporary jobs in construction and 23,000 full-time operational jobs [54].
- Economic effect: biogas improves the economics of the farmers, especially it requires a lower investment cost than other renewable energy sources [55,56].
- Environmental impact: biogas also has a lower environmental impact and higher energy yielding [56,57]. Moreover, the widespread biogas will decrease deforestation as it will produce a biofertilizer that is important for the land and reduce the usage of wood (cutting forests).
- Waste management: Biogas is an effective route for waste management, decreasing pathogens and odors, producing bioenergy, and bio-fertilizer [58].

Compared with fossil fuels such as natural gas, biogas is obtained from the biodegradation of organic materials using bacteria (biological process), while natural gas is naturally formed from fossils (geographical process). Methane represents up to 60% in biogas [59] and 90% in natural gas [60]. The calorific value of biogas is 5000 kcal per m^3 [61] compared to 8600 kcal per m^3 in the case of natural gas [61]. Moreover, biogas has lower environmental impacts compared to fossil fuels. For instance, per MJ energy, the CO_2 emissions from biogas is 81.5 g CO_2, compared to 682 gCO_2 and 139 g CO_2 in the case of coal and liquefied petroleum gas (LPG), respectively. Biogas also produces a 0.11 g CO compared to 26.2 and 0.82 g CO, in the case of coal and LPG, respectively [62]. Such properties indicate the promising features of biogas to replace natural gas in several applications such as:

- In rural areas, biogas is effectively used for cooking purposes; for instance, in China and India, biogas effectively replaces the different biomass sources and coal [63,64].
- Biogas can be upgraded into biomethane and then used as a fuel in vehicles and buses [65,66].
- Biogas can be used for combined heat and power applications in different energy capacities [58], i.e., microscale (Micro-scale anaerobic digester that will power a system of less than 15 kWe) [67], small scale ones with a power of 15 - 99 kWe [68], medium scale one between 100 and 299 kWe [69], and large scale capacities more than 300 kWe [70, 71].
- Biogas can be used as fuel for direct electricity generation in high-temperature fuel cells such as solid oxide fuel cells [72,73].
- Biogas can secure part of the energy demand in the different industries. For instance, in the sugar cane industry, biogas can be used for supplying energy in the distillation and the heat required for the vaporization of bioethanol [74], as a fuel for the agriculture machines used for the harvesting and the collection of the sugar cane [66], and supply the energy required for dying of the yeast [75].

From the discussion mentioned above, it is evident that biogas has several advantages compared with natural gas, and it is already demonstrated a high potential to replace natural gas in a wide range of applications starting from home usage to electrical generation at an industrial scale, including power plants.

2.3. Biogas impurities

One of the main obstacles facing the application of biogas is the contamination with various impurities, such as sulfur compounds, siloxanes, halogens, etc. Even after the biogas purification, the existence of traces of these impurities will result in the corrosion of the engine and other metallic parts. Eventually, extra costs would be required to maintain or replace the damaged parts [76,77]. Biogas contains a big fraction of CO_2, which decreases the energy density of the biogas fuel. Removing the CO_2, i.e., mechanization, to increase the energy density required extra equipment and energy [78,79]. Besides CO_2, biogas contains several critical impurities, such as sulfur compounds [80], siloxanes [81], halogens [82], volatile organic compounds [83], and ammonia [84]. The composition of the biogas, including these impurities, is dependent on the feedstock used in biogas production. Ullah Khan et al. [85] reported that the highest methane (60–70%) could be obtained using organic waste, followed by (58–65%) in the case of sewage, and the lowest percentage (45–62%) in case of landfills. Oxygen gas is reported to be as high as 1–5% in the case of organic waste, 1,2.6% in the case of the landfill, and less than 1% in the case of sewage. The highest H_2S content of 15–427 ppm was reported for landfill, 10–180 ppm for organic waste, and 0–24 ppm for sewage. While the highest organic impurities of Toluene and Benzene were in the case of landfills, followed by sewage, and the lowest in the case of the organic wastes [85,86]. Higher halogen compounds (less than 100 ppm) were reported for landfill, compared to less than 0.2 ppm for food waste, animal waste, or wastewater [87]. Table 2 summarize the main impurities in the biogas, their impact, and the different methods for their removal:

2.4. Challenges/barriers associated with biogas production

The conversion of the organic waste portion of the wastes into biogas has several socioeconomic benefits besides energy source, such as decreasing the environmental impacts, reducing the wastes that can be converted into leachate in landfills or bad smell/pathogens if left in the open areas, producing organic fertilizer, and securing jobs [119]. However, biogas facing several challenges such as:

- AD is a slow process requiring a long hydraulic retention time (HRT) of >30 days [120]. This raises the digester's volume and cost. Biogas output is also limited by low loading rates and slow recovery [121]. Optimal biogas production is at 37 °C; therefore, an efficient heat management system is required to get the maximum output. The temperature fluctuations over the year without proper heat management resulted in decreased biogas' productivity. Cold countries can find it challenging to adopt this technology due to a decline in biogas output during winter.

Although small levels of methane in the atmosphere don’t cause serious health problems, they strongly affect the environment [122]; biogas digester leakage raises CH_4 and CO_2 pollution into the atmosphere [123]. CH_4 is a powerful greenhouse gas that is 25 times that of CO_2, and it contributes around 20% of total global warming from the different greenhouse gases [124]. Such contributions of CH_4 in greenhouse gases increase global temperature and eventually the depletion of the ozone layer.

Table 2
The main impurities in the biogas, their effect, and the different methods for removal.

Impurities	Impact	Treatment method
Sulfur compounds:	Sulfur can exist in the biogas in different forms such as hydrogen sulfide (as a major form ranging from 500 to 4000 mg/liter) [88], CH_3SH, C_3H_7SH, C_4H_9SH, and/or dimethylsulfide [89]. H_2S and other sulfur compounds: corrosive, blocked the catalyst's active sites, and resulted in the deposition of elemental sulfur [90–95].	Chemical oxidation scrubbing, adsorption on metal oxides [95,96], membrane separation [97], or biological methods [98].
Halogens:	Halogens are the predominant contaminate in the biogas obtained from the landfill where it originates from the decomposition of the polymers and food salts [28]. Halogens such as chlorine compounds would result in forming HCL that eventually resulted in the corrosion of the metallic parts [99] or blocking the active catalyst, such as in the case of fuel cell applications [28,100].	Water scrubbing, AC adsorption, and condensation [90,101,102].
CO_2, N_2, and H_2:	The high content of these gases decreased the energy density of the biogas and increased the anti-knock characteristics in the combustion engines [90,94,95,103,104].	Absorption in water (water has a 26 higher absorptivity of CO_2 than CH_4) [105,106]. Chemical absorption using amines [107], adsorption, membrane separation [97]. CO_2 can be converted into methane, i.e., mechanization. However, extra equipment and will be required [78,79].
CO:	Carbon monoxide is highly toxic for people and some bioreactor microorganisms [90].	It is worth mentioning that CO is a fuel in some applications, such as solid oxide fuel cells [108].
H_2O:	Water vapor can result in forming corrosive acids such as H_2SO_4 and HCL in case of reacting with other compounds of the biogas. Also, it can be accumulated in the gas pipelines [90,94,95,109].	Adsorption using silica or activated carbon and condensation is commonly used [95,110,111].
O_2:	oxygen is corrosive, and if increased beyond a definite limit, it may result in an explosion [90,94,95].	Adsorption on the surface of silica or activated carbon, membrane, or carbon molecular sieve [95,112].
NH_3:	Ammonia formed due to the degradation of nitrogen-containing compounds such as protein [113]. Ammonia is a very corrosive gas, and also if burned, it will form NOx, which has a severe greenhouse gas effect [90,94,95,114].	Organic physical scrubbing (OPS) [115].
VOCs:	Volatile organic compounds have a bad smell and are corrosive, and some have a toxic effect [90].	Activated carbon is effectively used for the removal of VOCs.
Siloxanes:	Siloxanes are organic silicon compounds related to detergents, lubricants, etc., that exist in municipal solid wastes [116]. Biogas produced from wastewater sludge contains higher siloxanes than that of landfill [117]. The presence of siloxanes would result in the deposition of the SiO_2 that can inhibit the catalyst and block the gas pipelines.	Adsorption using activated carbon and silica gel, or absorption [95,118].

- Efficient biogas production requires a well-conditioned feedstock to enhance the life and activity of microorganisms. As such, biogas is suitable in rural and suburban regions as opposed to industrial ones [125].
- People often avoid using household digesters in the long run due to a lack of expertise, gas leakage, slow recovery, low gas demand, and an insufficient substrate supply [126]. There is a need for further research on these topics. Straw, for example, is a possible substrate for household biogas digesters, but further research and development are needed [127]. In general, the challenges of biogas are dependent on the scale of the digester and the country (developed or developing), as discussed below.

Small scale digesters: small-scale digesters are facing several problems, such as: gas leakages, lack of maintenance, shortage of feedstock, and blockages, which may eventually result in the end of the digester operation. It is estimated that 50% of digesters can be stopped due to the aforementioned reasons [128]. Methane emission does not only come from leakages but also in intentional release. Large-scale digesters are provided with flares that are used for burning the excess biogas. However, small ones are just released into the surrounding atmosphere [119]. Taking into consideration that the greenhouse effect of CH_4 is 25 times higher than CO_2; Bruun et al. demonstrated that a 40% leakage of biogas would result in a far worse environmental impact than that resulting from coal burning, as well as a 16% greater impact than that of liquid petroleum gas (LPG, mainly propane) [129].

Such worries can be eliminated through dependence on central anaerobic digesters (large scale ones) that will be provided with flare systems, efficient maintenance, minimum gas leakage, and cleaver operating staff. Despite the high risks of the domestic digester, they are still more preferable than landfill [119].

In biogas technology, the individual economic position is also an issue [130]. To suit the school's energy requirements, Sibisi and Green [131] built a floating drum digester. Adoption of biogas stoves and household biogas digesters is hampered in Thailand because of high expenditure, a lack of financial capital, information, and skilled labor [132]. Technological advancements will assist in resolving these issues by rendering biogas a viable source of energy in rural areas. Low biogas plant functionality due to faulty parts, a lack of technological expertise, failure to choose the appropriate scale and model based on location and raw material availability, inadequate monitoring, and a lack of non-profit organization (NGO) participation continue to be barriers to technology adoption. To train and educate farmers and local people about the potential of biogas technology, it is critical to spread simple awareness among them [133].

- As with all other renewable energy sources, the policies in place play a significant role in the widespread of biogas. Germany is the leading country in energy harnessed from biogas, and their success story stems from the Renewable Energies Act enacted in 2000 [134]. The policy was formulated to ensure that energy supply companies purchased electricity produced from renewables at the constant feed-in tariffs for two decades. With strong interventions put in place between 2004 and 2009 by the German government, the production of crops for energy skyrocketed, and this became a major boost for the biogas sector. Electricity generated from biogas is more expensive compared to that obtained from other types of renewable energies, especially without heat recovery [135]. This phenomenon tends to impact combined heat and power (CHP) valorization efficiency, as well as the economic viability of the biogas plant [136,137]. The setbacks that come with energy harnessed from biogas led to a review of the policies associated with harnessing energy via this medium in 2012.

> There was a need to reduce energy harnessed from maize, with feed-in tariffs being replaced by 2017 [136]. This became imminent to control the sector [137,138]. These policies directly affected the biogas sector, which led to a reduction in biogas production growth rate in 2018. Moreover, biogas as a medium of energy generation competes with other media of energy generation, like solar photovoltaics. Some biogas plants since 2012 have had their feed-in tariffs reduced despite the application of larger generators coupled with storage facilities on these plants. In 2020, most biogas plants developed in 2000 had their feed-in tariffs expire, and there were concerns regarding some plants being shut down in the absence of any novel policy being passed for biogas electricity.

Regarding the application of the policy, it may have an effect on the biogas whether it is applied in downstream or upstream as follow:

- In downstream:

Biogas is obtained from wastewater plants or waste management facilities (Municipal, agricultural, or industrial), where the safe disposal of the solid or liquid wastes requires considerable finance for such waste handling. The successful treatment of these wastes into biogas and bio-fertilizer will save the financial support that is required for their safe disposal. Such saving is considered an indirect income of the biogas. In addition to the direct value of the biogas and the bio-fertilizer, biogas is still economical, even without a subsidy of the downstream source.

- In upstream:

The policy will depend on the degree of the subsidy of the conventional fuel (natural gas and coal). So, if the cost of the biogas treatment from impurities is higher than the natural gas, this will negatively affect the usage of the biogas in the different applications. However, nowadays, the world is heading toward avoiding the subsidy of fossil fuels, eventually making biogas attractive. Moreover, the environmental impact of biogas compared to fossil fuels is still an attractive point for applying biogas instead of fossil fuels (natural gas).

In addition to the barriers mentioned above facing the biogas, Nevzorova and Kutcherov [139] conducted an interesting detailed analysis of all possible obstacles to biogas and their impact according to the country's status, i.e., developed or developing. The authors categorized the barriers into six main categories, i.e., technical, economical, institutional, market, socio-cultural, and environmental. Each category was also divided into several sub-barriers, as can be seen in Table 3.

As it is clear from the table, technical barriers are the most impactful in developing countries, at about 40%. This can be credited to the widespread of small-scale or domestic biogas digesters in developing countries that ordinary people, such as farmers operate. As such, the absence of technical operators is a significant concern. While in developed countries, industrial-scale digesters are the most

Table 3
Barriers facing the commercialization of biogas.

Barrier		Developed country	Developing country
Technical	Infrastructural	**8.74**	**9.01**
	Technical failures	0.97	4.66
	Lack of skilled staff	1.94	8.7
	Low level of collection and improper segregation	2.91	2.8
	Poor follow-up services	2.91	4.66
	Impurities	5.83	5.59
	Dependency on imported materials	1.94	3.11
Economic	High investments requirement	**7.77**	**11.49**
	Lack of subsidies and financial support programs	1.94	6.21
	High cost of biogas production, transportation, clean-up, and upgrading	5.83	2.17
	Absence of bank loans	2.91	0.31
	Lack of R&D	0.97	3.42
Market	Lower prices of fossil fuels	**4.85**	1.86
	High price of biogas	2.91	0.62
	Competition with other fuels	0.97	1.24
	Uncertainties related to injection of biogas into the grid	3.88	0.31
institutional	Lack of political support	1.94	6.21
	Uncertain policy landscape	**11.65**	1.86
	Lack of private sector participation	2.91	3.11
	High level of bureaucracy	8.74	0.93
Socio-cultural	Lack of public participation and consumer interest	4.85	**6.52**
	Resistance to change	0	1.24
	Low level of knowledge	3.88	1.24
	Lack of information and information sharing	0	2.17
	Low level of education	0	1.24
	Cultural and religious outlook including stigmatization	0	3.11
	Migration	0	0.62
Environmental	Odor complaints	**4.85**	0.62
	Noise complaints	1.94	0
	Need for abundant water resources for biogas digesters/Lack of access to adequate water	0	**4.35**
	Pollution	1.94	0.62

The percentages of each subcategory are calculated based on how many are mentioned in reference to each main category in the literature used in the study done by Nevzorova and Kutcherov [139].

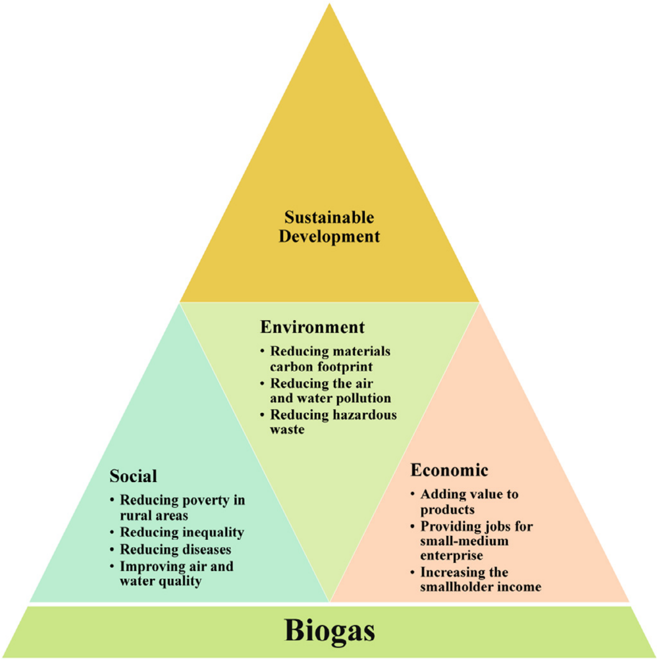

Fig. 3. Biogas interlinkage to contribution into sustainable development goals.

common ones, where trained staff is available. The insufficient support of the government in terms of subsidies and the absence of knowledge in the sector are also major concerns in developing countries. However, the biogas market in developed countries is challenged by a lack of the end-user distribution system, the competition with fossil fuel prices, the absence of a fixed policy "usually affected by the political situation", and finally, the environmental impact.

3. Contribution of biogas into SDGs

The following section describes 1) the contribution of the biogas to the three pillars of sustainable development, i.e., economic, social, and environmental, Fig. 3; 2) a detailed contribution of the biogas into the SDGs and sustainable development dimensions (SDDs), Table 4; 3) the advantages and limitations of biogas with their linkage to SDGs, Fig. 4.

3.1. Increasing renewable energy production (SDG 7: affordable and clean energy)

Across the globe, coal, natural gas, and petroleum products are mainly used as a source of heat and power production. Biogas, derived from organic waste and agricultural by-products, replaces fossil fuels and decreases carbon dioxide emissions. Biogas is

Table 4
Contribution and interlinkage of biogas to sustainable development goals (SDGs) and sustainable development dimensions (SDDs).

SDG	Contribution of Biogas	SDD
SDG 1: No Poverty	✓ Assisting the smallholder by providing affordable fertilizer and eliminating the issues of the complexity of the fertilizer supply chain [140]. ✓ Generating jobs by adopting a new business.	***Economic***
SDG 2: Zero Hunger	Improve agricultural productivity by: ✓ Enhancing the soil condition by recovering lost nutrients, organic matter, and carbon. ✓ Increasing the yields by providing reasonably priced fertilizer. ✓ Recirculating phosphorus (P), nitrogen (N), potassium (K) throughout the digestion process [141].	***Economic***
SDG 3: Good Health and Well-being	✓ Reducing the exposure to a few hazardous materials by burning the biogas [142]. ✓ Reducing methane emission [143].	***Social***
SDG 4: Quality Education	Increasing energy accessibility in rural areas will improve the quality of education.	***Social***
SDG 5: Gender Equality	Provides an affordable source of energy to the local communities in the rural area which leads to improving the quality of life of women and children [144].	***Social***
SDG 6: Clean Water and Sanitation	✓ Improving the quality of the water by increasing wastewater treatment capacity due to energy availability[145]. ✓ Providing decentralized wastewater treatment facilities in rural area.	***Environment***
SDG 7: Affordable and Clean Energy	✓ Increasing overall energy sustainability. ✓ Increasing energy supply reliability and affordability [85]. ✓ Increasing the energy storage capacity.	***Environment***
SDG 8: Decent Work and Economic Growth	✓ Increasing the gross domestic product (GDP) by enhancing waste utilization [146]. ✓ Reducing materials carbon footprint [145,147,148].	***Economic***
SDG 9: Industry, Innovation, and Infrastructure	✓ Build a sustainable infrastructure [149]. ✓ Providing energy for a small-scale industrial rural area [150]. ✓ Adding value to the waste by converting it to biogas (energy).	***Economic***
SDG 11: Sustainable Cities and Communities	✓ Preventing the diseases through gathering the organic waste and treatment of wastewater [151]. ✓ Improving the air quality by reducing the bad odor [152]. ✓ Increasing electricity accessibility [153]. ✓ Improving the waste management process [154].	***Social***
SDG 12: Responsible Consumption and Production	✓ Enhancing the efficiency of natural resource usage. ✓ Reducing air and water pollution [155]. ✓ Improving the waste recycling process [156].	***Environment***
SDG 13: Climate Action	✓ Reducing GHG emissions by providing a lower-emission energy source. ✓ Reducing methane emissions from the livestock industry [157]. ✓ Reducing GHG emissions from landfills [158].	***Environment***
SDG 14: Life Below Water	✓ Reducing marine pollution by preventing land source pollution.	***Environment***
SDG 15: Life on Land	✓ Reducing deforestation by replacing solid fossil fuels with biogas. ✓ Improving the freshwater ecosystems by enchanting the wastewater treatment [159]. ✓ Improving land-use productivity and reducing land-use change [160].	***Environment***
SDG 16: Peace and Justice Strong Institutions	There are several studies that suggested that rising power availability is directly linked to peace [161].	***Social***

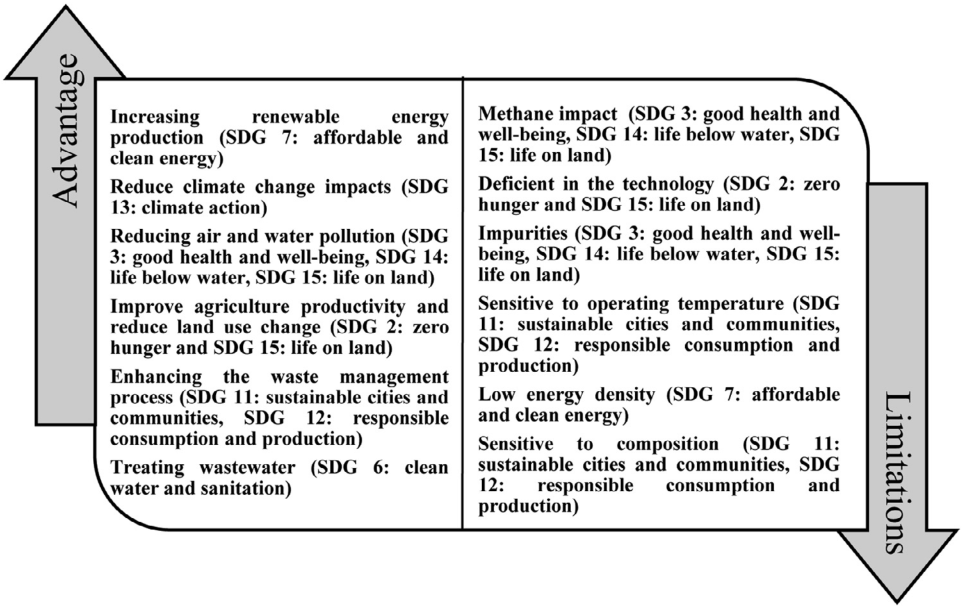

Fig. 4. Biogas advantages and limitations with their linkage to SDGs.

considered a renewable energy source that does not have geographical limitations and requires complex technology [162]. Biogas provides an incentive for energy generation to be decentralized and democratized. Rural and remote communities that are not linked to electricity and gas grids can generate their own energy (from biogas) using the waste they generate. Thus, they can become self-sufficient in terms of energy/resources. Biogas can be stored inside a digester, in a small-scale gasholder, or injected into an existing gas grid when excess gas is available. It can, therefore, be used in combination with other energy-producing technologies to satisfy both baseload and peak energy requirements.

Although the positive role of biogas as an affordable clean energy source, it also comes with negative effects, such as the role of methane in the greenhouse gases, impurities that can result in decreasing and even destroying the devices, low energy density, and fluctuations in the amounts and composition, etc.

3.2. *Reduce climate change impacts (SDG 13: climate action)*

Global warming is one of the world's most pressing environmental issues. In the past, unsustainable oil use led to global change, which must be resolved [163,164]**.** Unlike fossil fuels, biogas has few negative environmental impacts and produces few harmful emissions. Fossil fuels contribute toward GHG emissions, which are the major reason for climate change, global warming, and the melting of polar ice. Fossil fuels, as well as land-use change, contribute 33×10^{15} and 38×10^{15} tons, respectively of GHG annually [165]. Desertification, greenhouse gas pollution, soil degradation, and depletion of the cultivated area may all be reduced by using anaerobic digesters, i.e., household digesters.

Biogas is a cleaner form of energy and does not produce poisonous, harmful gases. As biogas is a localized energy source, no threat from its transportation will be imposed on the environment. As CO_2 is produced during the combustion of biogas, plants will use this biomass during photosynthesis (biomass), and this biomass will be used for biogas production. Therefore, the overall CO_2 emissions cycle of biogas and other biomass resources is closed or nearly zero. In the transportation sector, it is expected that the use of biogas instead of fossil fuels can reduce GHG emissions by 60–80%, from IRENA (https://www.irena.org/-/media/files/irena/agency/publication/2017/mar/irena_biogas_for_road_vehicles_2017.pdf). Global CO_2 emissions can be reduced by 18–20% by using biogas for the local community's electricity production and space heating. The Intergovernmental Panel on Climate Change (IPCC) stated that 14% of world GHG emissions are contributed to by the transport sector [5]. Based on Food and Agriculture Organization (FAO) data, livestock emissions, primarily in carbon dioxide, methane, and nitrous oxide, account for 14.5 percent of overall anthropogenic GHG emissions [166]. Via anaerobic digestion (AD), the treatment of manures decreases the formation of nitrous oxide and captures methane as biogas, which can be used for generating electricity.

In the Chinese province of Henan, Hamburg [167] conducted a pilot-scale analysis on the emission of H_2S and SO_2 through cooking with crop stalks, coal, and biogas. The study results demonstrated that the SO_2 emissions from crop stalks and coal were four times higher than those from biogas. Furthermore, no detectable levels of H_2S were discovered in the case of the biogas. Yu et al. [63] conducted a systematic analysis to examine rural energy production in China utilizing household-scale biogas digesters and greenhouse gas emission reduction. Straw, fuelwood, biomass, refined oil, power, liquefied petroleum gas (LPG), natural gas, and coal gas pollution were related to emissions from biogas. Subject to the volume of demand from 1991 to 2005, biogas as a replacement for other energy sources cut greenhouse gas emissions by ***73.157 megatons*** CO_2 equivalents. According to Zhang et al. [168], more than 420,000 premature babies die in China each year due to indoor air pollution. Most emissions are caused by inefficient burning fuels and released greenhouse gases. The majority of these diseases are caused by contamination from cooking. On the other hand, biogas is a cleaner fuel than biomass or coal combustion. When biogas is used for cooking, cleanliness applies to the cooking vessel not becoming black in the vessel's bottom. Since biogas contains less long hydrocarbons, it can produce fewer emissions. Headaches, dizziness, blurry vision, nausea, and vomiting are all symptoms of increased hydrogen sulfide concentration. Another research in the Peruvian Andes, which included 12 remote families in a project to replace firewood with biogas, found that firewood use was reduced by 50–60%, and cooking time, was reduced by 1 h [276]. The findings are focused on a survey that involved technological aspects such as a form of fuel, cooking time, environmental aspects.

Cattle dung is commonly utilized as manure or dung cakes in the kitchen, which is neither hygienic nor cost-effective [169]. Burning dung cakes not just pollute the environment but also wastes a beneficial fertilizer (if added directly to the ground) [170]. Anaerobic digestion is a safe and profitable method of removing this cattle dung [171]. According to Hiremath et al. [172], India may fulfill its energy demands by decentralized energy planning and using locally available resources. Biogas is one of the potential energy-generation options for India.

One-third of India's dung is adequate to power 12 million biogas plants [173,174]. The use of biogas digesters by rural people may support them financially and improve their living standards, such as better air quality and better health [175]. For example, cooking with firewood produces a lot of smoke and soot particles. Smoke and soot add to air contamination, which leads to health problems like respiratory disease [175]. Renewable energy supply for remote uses and adequate sanitation make a big difference in parasitic disease control [168,173]. Although collecting the biogas will minimize the methane emissions in the atmosphere, small amounts of methane strongly affect the environment [122]. Methane is a powerful greenhouse gas that is 25 times that of CO_2, and this why it contributes around 20% of the total global warming from the different greenhouse gases [124]. Such contribution of the methane in the greenhouse gases will not only increase the global temperature and its associated problem, but it will also result in the depletion of the ozone layer that protects the universe from harmful waves such as ultraviolet waves. However, by comparing houses with and without biogas systems and considering the gas leakage in the biogas systems, it was discovered that homes with biogas plants emit 48 percent less than homes without biogas plants [176]. It's worth noting that methane leakage was found in just 10% of households [177].

The landfill contains a large amount of methane gas. Methane gas is 55% of the total volume of landfill gas. This amount of harmful gas needs to be prevented from escaping into the air; otherwise, it will contribute to global warming and climate change. Biogas trapping of landfills is therefore of significant importance [178]. One of the side effects of the biogas is sensitivity to the composition. Whereby the efficient biogas production requires a good portion of manure and food waste to enhance the life and activity of the microorganisms. Therefore, biogas is suitable in rural and suburban regions compared to industrial ones [125].

3.3. Reducing air and water pollution (pollution prevention) (SDG 3: good health and well-being, SDG 14: life below water, SDG 15: life on land)

The biogas industry can help reduce air and water pollution, which is mainly related to the local production of the biogas/biomethane, so there is no need for transportation using ships that had a severe impact on aquatic life [179]. Biogas can replace fossil fuel in gas power plants, transport fuel in gas vehicles, capture emissions from municipal solid waste, and turn it into valuable energy. The burning of fossil fuel contributes a large amount of fine particulate matter, which pollutes the air. Replacement of fossil fuels, especially coal, may significantly reduce CO_2 emissions and fine particulate matter. Reduction in air pollution means that the extent of acid rains will also decrease, resulting in less water pollution. Oxygen demanding organisms in wastewater can reduce the oxygen level in surface water. Production of biogas from wastewater not only reduces the pollution potential of wastewater, but also the slurry obtained from biodigester can be used as fertilizers due to its high content of nitrogen and phosphorus [180,181].

The extraction of landfill gas from active and closed landfills and the conversion of excess organic waste to anaerobic digestion (AD) would result in decreased pollution, digested recirculation of nutrients, and the use of biogas for power generation [182–184]. In addition, indoor air pollution is caused mainly by firewood, crop residues, dried animal dung, and crop waste as domestic fuel. Furthermore, firewood is one of the leading causes of deforestation, leading to greenhouse gas accumulation. As a cooking fuel, the use of biogas produced externally from the digestion of domestic and agricultural waste can reduce indoor air pollution and decrease deforestation [185].

The digestion of the organic part of the industrial effluents, such as those from palm oil mills, breweries, slaughterhouses, etc., into biogas, will minimize the environmental impacts of these processes and generate energy for their operations, thus increasing their sustainability and self-reliance [186,187]. By providing decentralized and local care of these wastes, AD of biosolids encourages a sanitary and hygienic climate. This helps to avoid diarrheal diseases such as cholera, trachoma, schistosomiasis, and hepatitis from bacterial infections [188–189]. One of the main obstacles of the biogas is that it contains various impurities such as sulfur compounds, siloxanes, halogens, etc. Even after the biogas purification, the existence of traces of these impurities will result in the corrosion of the engine and other metallic parts. Eventually, the extra cost was required for maintenance and replacing the damaged parts [76,77]. Novel pre-treatment methods are required to remove such pollutants easily, cheap, and effective.

3.4. Improve agriculture productivity and reduce land-use change (SDG 2: zero hunger and SDG 15: life on land)

The potential of bioenergy is huge, but somehow, it is not infinite as for biomass production. The land available is not unlimited rather limited. That limited land is also under conflict due to biomass competition with food crops. Most Governments have political goals to increase the renewable energy share in the future. This competition has intensified the land-use issue [190]. Land use is of significant importance as land helps control and maintain many natural processes like carbon fixation, water maintenance, nutrients cycle, decomposition of harmful matter, and conservation of genetic resources [190,191]. The use of chemical fertilizers is hazardous in terms of disposal and land fertility as chemical fertilizers kill pests and soil-friendly microbes. Land availability is already limited so that soil infertility can cause a food shortage. The territorial ecosystems and agriculture crop yield have been adversely affected by soil degradation in the recent past. Mining is done to extract gas and fossil fuels to meet the energy demand for cooking, electrification, and transportation [192].

Similarly, mass biodiesel and bioethanol production using energy crops and vegetable oil lead to land-use change conflicts and food scarcity issues. Using first-generation feedstock like sugarcane and seed oils for bioethanol and biodiesel could lead to food scarcity. This could also increase essential staples prices as a significant part of the world food supply comes from starch, sugar-rich cereals, and grains. Gevo, Inc., installed a biofuel production plant in Minnesota to supply aviation fuel to Scandinavian Airlines Systems. Gevo contributes 8 pounds of protein corresponding to each biofuel gallon production. This 8-pound protein per biofuel gallon production is a step to add to the food supply and chain. Thus, Gevo is committed to producing biofuel and food production to avoid food scarcity. However, this would not be enough as there are more serious challenges and hurdles on the road to bioenergy [193]. When crop residue like wheat straws, rice husk, and cotton sticks are left in the field, they add nutrients and organic carbon to the soil. When there is no residue left in the field, and they will be used for bioenergy production, this may cause erosion of top fertile soil. Reduction in soil fertility will affect the average yield of food crops and could result in a shortage of cereals, grains, and food [194].

Biogas production provides a solution to all of these land-related issues. Biogas can be used as cooking gas, transportation fuel, and electricity production, so there is no need for land mining to extract fossil fuels. Biogas produced from animal manure can be used as a transportation fuel to replace bioethanol and biodiesel, which are controversial due to land competition with food crops. The slurry produced as a by-product of AD is used as a bio-fertilizer, which will increase land fertility and agriculture production [195–197]. The solid and liquid fractions left over after digestion of the feedstock can be used as an organic modification/soil improver (digestate or composted digestate biofertilizer) on farms instead of energy-intensive chemical fertilizers. The use of digestate biofertilizer has proven and verified results to increase crop yields [198,200].

To stimulate the growth and maturity of plants, phosphorus is commonly used in agriculture. Phosphorus is lost to surface water bodies due to inefficiencies in use, inducing harmful algal blooms. It is possible to market phosphorus recovered from dewatering liquors leftover from wastewater digestion and use it as biological struvite on farmland [201]. Desertification of land can be avoided and reversed by recycling the nutrients in the soil through the AD of primary crops, breaking and catching crops and organic waste, and returning them to the soil in the form of digestate biofertilizer. In order to ensure food security, this is a crucial step [202].

3.5. *Enhancing the waste management process (SDG 11: sustainable cities and communities, SDG 12: responsible consumption and production)*

About 4 million deaths and 110 million life-year adjusted disabilities have been due to exposure to domestic solid biomass fuel-burning pollution. The resulting emissions include black carbon, a short-lived climate pollutant that is known to interrupt monsoons and accelerate glacier melting, threatening the masses with water and food security. Burning biogas instead of biomass will reduce residents' exposure to a number of these contaminants, thus enhancing their well-being and health [202,203]. Advancement in industrial processes, enhanced commercialization, and urbanization are resulting in diversified chemical and solid waste, the harmless disposal of which has become a challenge [204]. Sustainability in municipal solid wastes (MSW) means the collection of MSW and its either proper disposal or conversion into useful products [205,206]. The huge quantity of waste provides an opportunity to use this waste either as direct land application, as construction material, or can be converted into biogas through anaerobic digestion [207].

The government can provide incentives to support a waste-to-energy conversion plan. Instead of throwing away the garbage, the public will sell the garbage to companies working in waste to bioenergy treatment plants [207]. Decentralized and local treatment of waste to produce biogas via AD improves the hygienic environment and protects from bacterial infection. Improper management of landfills can give a ride to many fatal diseases such as dengue fever etc. Also, disposal of waste requires land area, which is not viable economically. Installation of the biogas power plant will help cope with waste management issues and better energy security. Also, the human population is increasing so the livestock market is also growing to meet the needs of this population. This increased amount of livestock means more challenges in its disposal. Biogas is mainly produced using livestock waste, especially cow dung that pollutes the environment if directly burned in cooking, increasing the suspended particle amount in the air and causing air pollution [208].

Diversion of organic matter from landfills not only provides a way to mitigate pollution but is also responsible waste management practice, with ever diminishing landfill space and the environmental threat it presents to nearby soil and groundwater. To avoid the spread of diseases such as leptospirosis, plague, dengue fever, and other bacterial and viral diseases transmitted by mosquitoes, flies, rodents, etc., and to improve air quality in landfill communities, proper management of organic waste is necessary [209].

3.6. *Creating jobs, improving economic development, and adding value to products (SDG 9: industry, innovation and infrastructure, and SDG 8: decent work and economic growth)*

Biogas can contribute positively to economic growth as it has diverse effects as summarized in Fig. 5. About 3 billion people worldwide are estimated to rely on solid biomass fuels such as dried dung cakes, firewood, crop residues, heat and cooking straw, or other agricultural residues [210]. In developing countries, the burden of gathering firewood and exposure to air pollution from domestic cooking is mainly placed on women and children. As a domestic fuel, the introduction of AD and biogas could positively affect the quality of rural life and is already widely used in countries such as Bangladesh and India. Biogas is a source of energy, which is critical for economic growth [148,211]. Adding value to the waste will change it from a burden on the government into an opportunity to produce biogas,

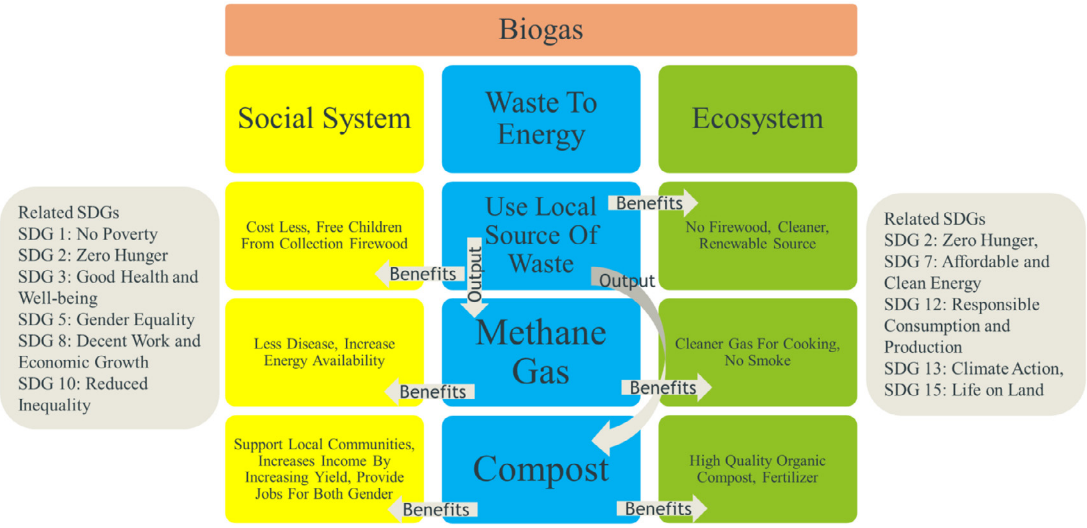

Fig. 5. Impacts of biogas production on the social system and ecosystem with the related SDGs.

bio-fertilizer and create new jobs. For instance, although biogas represented less than 2.2% of that total renewable energy in 2019 (based on the American Biogas Council (ABC)), biogas business has created about 335,000 temporary construction jobs and 23,000 full-time operational positions [54]. In China, biogas alone supports 209,000 workers [54], and biogas has great potential to grow up in the next few years. Such a number of jobs is acceptable compared with those in the other renewable energy sources, i.e., 1165,000 in the wind, 99,000 in the case of the geothermal, 3,755,000 in the solar, and 1100 in the case of the tidal [54]. If the slurry from biogas digesters is not correctly utilized, it becomes an active breeding ground for insects that transmit disease [167]. The slurry from biogas plants can be utilized to grow earthworms. Slurry combined with plant-rich materials may also be used as a vermicomposting base [212–215]. Also, this slurry contains humic acid and acts as an excellent soil conditioner [195,196]. The economic benefits of biogas have been extensively discussed in the literature [183,216–218].

Although there are enormous benefits associated with biogas, it is no exception from some drawbacks, too, as it finds its significance in rural areas because, in rural areas, raw material for biogas is readily available. Despite being relatively less expensive, these plants are not affordable for middle and lower-class farmers. The technology being used for biogas production still needs to be advanced and matured [219].

The development stage and challenges of the biogas are different between developed and developing countries. In developed countries, the biogas industry is already well established, and most of the challenges are on the policy side [143]. While in developing countries, the biogas industry is still in the early stage of implementation [143,220] and still facing many challenges, such as the absence of sufficient technical and infrastructural, sufficient capital, and poor policy [221,222]. Based on the recent data from IRENA (https://www.irena.org/Statistics/View-Data-by-Topic/Benefits/Renewable-Energy-Employment-by-Country), most of the jobs created, per capita, by the biogas industry were on the developed, as shown in Fig. 6. However, job creation increased in recent years, indicating that biogas can create sustainable jobs in the future. Moreover, the development of biogas in developing countries will keep increasing in the near and long term [223].

3.7. *Treating wastewater (SDG 6: clean water and sanitation)*

There are many methods for water purification that include: purification of seawater [224,225], reverse osmosis process [226,227], desalination systems [228,229], urea fuel cells [230,231], bio-electrochemical systems [232,233], and others for water purification [234–236]. Biogas produced from wastewater anaerobic digestion can be used in a diesel engine to produce electricity. This electricity will be used to run this water treatment process to make it drinkable. However, a sustainable plan for wastewater treatment was a big challenge, and it will be. Treating wastewater will reduce GHG emissions, water pollution, and threats to aquatic life and will improve people's economics and quality of life where these wastewater treatment plants will be installed. This plan will satisfy a diverse range of sustainable development, including social, environmental, and economic [237]. The wastewater treatment plants must be able to consider the effectiveness of capital and operating cost, efficient use of energy, and discharged water must be safe for the environment [219]. Suppose efficient use of biogas is made along with the efficient plant plan. In that case, the requirement of internal energy for wastewater treatment can be provided by the biogas produced from wastewater [238–240]. The wastewater treatment using biogas can be further economical by increasing the load and biomass of micro-organisms [241].

AD can be used in those areas of the world where biosolids are collected and processed in wastewater treatment plants to stabilize sewage sludge before being applied back to agricultural land as a biofertilizer [242,243]. AD lowers the water's carbon load and, thereby, if discharged, makes wastewater less toxic to aquatic bodies and life [244]. In terms of economy and electricity, digestion of solid organic waste and wastewater will make these treatment facilities self-sufficient. Small-scale, decentralized care options are being built and applied where the collection infrastructure is unavailable. Although there are enormous benefits associated with biogas is no exception from some drawbacks, too, as it finds its significance in rural areas because, in rural areas, raw material for biogas is readily available. Despite being relatively less expensive, these plants are not affordable by middle and lower-class farmers. The technology being used for biogas production still needs to be advanced and matured [219].

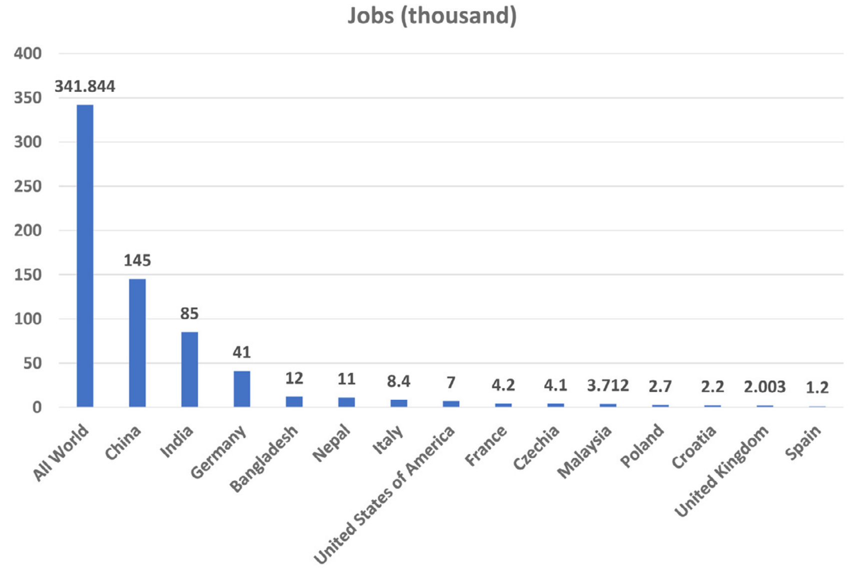

Fig. 6. Total job created by biogas (data used for this figure was obtained from https://www.irena.org/Statistics/View-Data-by-Topic/Benefits/Renewable-Energy-Employment-by-Country).

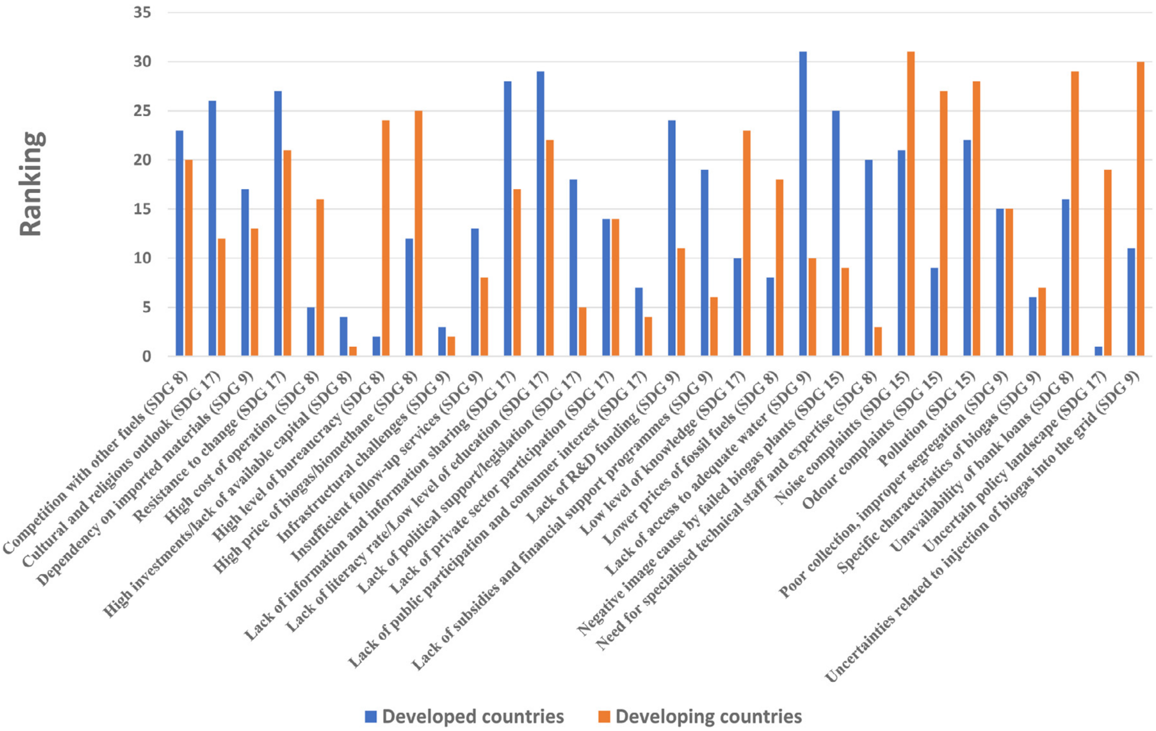

Fig. 7. Presents ranking of the different barriers of the biogas in developing and developed countries linked to the related SDGs. Data used for this figure was from [139] permission from Elsevier "license No. 511,668,045,596".

4. Barriers of the biogas in connection with the SDGs

Nevzorova and Kutcherov [139] have listed a total of 31 barriers that facing the implementation of biogas. They found different the impact of these barriers is different in the developed and developing economies. The major barriers for developing countries are:

- High investments/lack of available capital.
- Infrastructural challenges.
- Need for specialized technical staff and expertise.
- Lack of public participation and consumer interest.
- Lack of political support/legislation.

While for the developed countries, the significant barriers are:

- Uncertain policy landscape.
- Infrastructural challenges.
- High level of bureaucracy.
- High investments/lack of available capital.
- Specific characteristics of biogas.

Fig. 7 presents the ranking of these barriers between developed and developing nations linked to the related SDGs. Data used for this figure was from [139]. The analysis shows that the most challenging barriers in developing countries are related to SDG 8: Decent Work and Economic Growth followed by SDG 9: Industry, Innovation, and Infrastructure. In the case of the developed nations, the most significant challenges were related to SDG 17: Partnerships to achieve the Goal and SDG 9: Industry, Innovation, and Infrastructure.

5. Biogas SDGs indicators

Based on the above analysis and several literature works [245–247], a total of 58 indicators were created, shown in Table 5. The purpose of these indicators is to make sure that the biogas project delivers a balanced constitution to all the SDGs and assists in achieving the SDGs. Besides the main benefits of the proposed indicators, there are several benefits, which can be summarized as follows [247]:

- Improve sustainability performance.
- Enhance risk management and stakeholder communications.
- Engage stakeholders and improve stakeholder relations.
- Improve internal data management and reporting procedures.
- Benchmark sustainability performance against self and others.
- Improve resource allocation.
- Cost reduction.
- Reduce the climate change impact and environmental impact.
- Reduce social inclusion.

6. Contributions to knowledge

The use of biogas as a cooking fuel for low-income countries would be an efficient means of eradicating poverty and hunger and providing clean and affordable energy. Lohani et al., [32] evaluated the current biogas potential and usage in Nepal. The analysis covered 431,000-biogas plants installed throughout Nepal- where only 1% of the biogas was converted to useful energy. The authors concluded that biogas plants used in Nepal would significantly contribute towards increasing agricultural productivity by providing more time for people to work on agricultural lands, as well as reduce health impacts by providing clean energy, empowering women and girls by giving them time for education by reducing their time for collecting firewood, providing clean and affordable cooking fuel and energy, mitigate climate change by reducing greenhouse gas productions and providing a way to protect forests. The authors also reported that small-scale biogas systems would contribute to the achievement of the SDGs 1: no poverty, SDG 3: good health and well-being, SDG 5: gender equality, SDG 7: affordable and clean energy, SDG 13: climate action, and SDG 15: life on land. Meeks et.al., [248] demonstrated that biogas over fuel-wood collection as a fuel-wood collection is time-consuming. With more time, rural people will move away from

Table 5
SDGs biogas indicators.

SDGs	Indicators
Goal 1. No poverty	1. Total Taxes paid.
	2. The number of employees.
	3. Average employees' salary.
	4. Number training programs per employee,
	5. Paying decent prices to all suppliers, in particular micro, small and medium enterprises.
	6. Lowering utility costs, such as water and electricity, for the low-income community.
Goal 2. Zero hunger	7. Nature of land occupied by biogas facility (arable/nonarable).
	8. Disaster risk management policy.
	9. Documents hazard substances used.
	10. Total nutrients, organic matter, and carbon recycling.
Goal 3. Good health and wellbeing	11. The number of accidents during biogas building/operation.
	12. Dust control measures.
	13. Total healthcare benefits given to the employees.
	14. Calculating human toxicity potential, particulate matter and, photochemical ozone creation potential.
Goal 4. Quality education	15. Availability of assessment programs to test employees' skill levels.
	16. The average number of training programs conducted per employee.
	17. Abolition of all child labor.
Goal 5. Gender equality	18. Percentage of women recruited and employed.
	19. Income paid to women.
	20. Percentage of leadership positions occupied by women.
Goal 6. Clean water and sanitation	21. Water pollution and water reduction, wastewater management, and circular water strategies.
	22. Water consumption.
	23. Nonportable water consumption.
	24. The total reduction in water consumption.
	25. Decrease the water footprint.
	26. Quantifying freshwater aquatic ecotoxicity potential and eutrophication potential.
Goal 7. Affordable and clean energy	27. Conducted an energy balance analysis.
	28. Degree of energy sharing.
Goal 8. Decent work and economic growth	29. The investment in clean technology research and development.
	30. Pay of goods from local the communities.
	31. The proportion of housing offered to temporary employees.
	32. Employment creation.
Goal 9. Industry, innovation, and infrastructure	33. Conducted social, economic, and environmental impact assessments.
	34. Applying circular business concept.
	35. Tracking and reporting climate impact.
	36. Overall value-added.
Goal 10. Reduced inequalities	37. The proportion of training programs for marginalized populations.
	38. Total wage disparities between different working groups.
	39. Level of diversity and inclusion.
Goal 11. Sustainable cities and communities	40. Resource's sustainability strategies.
	41. Participation in microgrids.
	42. Overall produced waste.
Goal 12. Responsible consumption and production	43. Tracing all types of short-term and long-term pollution, such as GHG, methane, and water pollution.
	44. Overall resources and materials required.
	45. Overall waste treated.
	46. Materials (phosphorus, nitrogen) recycling potential
Goal 13. Climate action	47. Reporting all the types of pollution.
	48. Location of the facility.
Goal 14. Life below water	49. Tracking and reporting all water-related pollution.
	50. Quantifying the marine ecotoxicity.
Goal 15. Life on land	51. Quantifying biodiversity the impact.
	52. Effective methane yield
Goal 16. Peace, justice, and strong institution	53. Anti-bribery management systems.
	54. Stakeholders' engagement.
	55. Level of compliance to projects' directives and provide transparent information.
	56. Sum of environmental violations
Goal 17. Partnerships for the goals	57. SDGs' incorporation in business strategies.
	58. Collaboration with the different agencies.

home production and work on wages, agricultural land, and education. This shift in work from home production to agricultural land and education will result in growth of economy. Similarly, no forest disruption will be done to gain fuel-wood, which will help in mitigating climate change. Moreover, they found that biogas is beneficial for the socio-economic growth of Nepal, where high-wage jobs are given to skilled individuals, as well as better forest policies implemented. The work was linked to many of the SDGs, but were mainly linked to SDG 1: no poverty, SDG 2: zero hunger, SDG 3: good health and well-being, SDG 7: affordable and clean energy and SDG 15: life on land [248]. In another work, Shaibur et al. [33] evaluated the cow dung to generate biogas and its effect on the sustainable development of a district in Bangladesh. The authors concluded that the biogas plant provides an efficient way to convert cow dung into useful energy and fertilizer, reducing the cost of purchasing fertilizer. It also enhanced the cooking environment for biogas digesters, which would eventually decrease the time required to collect wood for cooking food, providing people ample time to attain education and work elsewhere. The authors also suggested that the use of biogas plant for cow dung would eventually improve the environmental conditions and socio-economic profile of the district. The study showed a direct linkage with SDGs 2: zero hunger, SDG 7: affordable and clean energy, and SDG 15: life on land. In other work, Rahman et al., [35] provided a conceptual model for using anaerobic digestion as a means to achieve

SDGs in rural areas of Bangladesh. The authors concluded that using anaerobic digestion will enhance the well-being of people by reducing green-house gas emission and air pollution, empowering women by providing them time to study other than household work and by generating clean and affordable by generating energy, bio-fertilizer and clean cooking fuel. The authors concluded that implementing biogas will help realize a number of the SDGs, namely, SDG 3: good health and well-being, SDG 4: quality education, SDG 5: gender equality, and SDG 7: affordable and clean energy. Also, Rosenthal et. al., [34] showed the importance of how clean cooking can help to achieve sustainable development goals. The authors did a comparison between solid fuel combustion and cleaner fuels, including liquefied petroleum gas (LPG), ethanol, and biogas. The biogas and liquefied petroleum gas (LPG) operating stove reduced air pollution, resulting in mitigation of climate change and providing better health conditions. The results demonstrated that by switching towards biogas and LPG, better environmental (SDG 13: combat climate change, SDG 15: sustainably manage forests and halt land degradation), health conditions (SDG 3: health and well-being), and gender equality (SDG 4) and access to reliable, efficient modern energy (SDG 7) could be achieved [34].

The industrial use of the biogas bio-refineries would be an essential way to enhance sustainability [249]. Biogas provided solutions in product valorization and material upcycling in bio-refineries in Swedish settings. Based on the findings, the use of biogas would help reduce deforestation (SDG 15), wastewater treatment (SDG 6), enhance marine life (SDG 14) and provide better agriculture and rural life (SDG 2). The paper did not elaborate on the contribution of the biogas to the SDGs; the focus was given to sustainable development, which can be linked to the SDGs. Dada and Mbohwa [250] demonstrated that using organic waste in landfills, the anaerobic digestion would provide biogas and bio-methane for various applications. Similarly, it would also provide a way to mitigate fossil fuel use, which lessens the adverse effects on the environment [250]. The authors emphasized on the linkage between biogas and SDG 7: affordable and clean energy.

Biogas production from agriculture residues was reported by Orner et.al. [36]. The authors reported that the biogas from agriculture residues and animal manure would provide a way to enhance water quality and sanitation, provide bio-fertilizer, which will reduce ground water degradation, improve the environment, provide food security, and help secure ecological systems, like forests [36]. The main focus of the paper linked biogas with SDG 6: clean water and sanitation. Also, Sahota et al. [39] discussed biogas applications as a potential alternative renewable energy technique to fulfill the SDGs. The authors presented the state-of-the-art techniques available for biogas. They concluded that biogas could be a potential contributor to vehicular fuel or generating electricity and provide carbon emission reduction and better energy efficiency [39]. Recently, Chrispim et al. [251] proposed an assessment to evaluate biogas issues from wastewater treatment plants. The proposed strategy would provide better energy efficiency and reduce greenhouse gas emissions, along with better waste water treatment. However, a lack of government subsidies and a biogas market are required to further increase biogas for wastewater treatment [251].

As can be noticed from the above and other literature [37–39], biogas has an undeniable positive contribution towards achieving various SDGs. Most of the studies did not provide a clear linkage between biogas and the SDGs. Almost all studies focused on improving the biogas technology and linking the biogas to a special SDG. Providing the linkage between the different SDGs and biogas andrecognizing the limitation of the biogas; the decision and policymaker will be able to increase the contribution of the biogas into the SDGs and thus reduce any possible trade-off is done in this work. The developed indicators or guidelines will ensure that biogas contributes to the SDGs and most of the trade-offs are minimized.

Biogas production has been found to impact directly and contribute to most SDGs, more specifically, as an affordable and clean energy source that can drive the achievements of many other goals, such as clean water and sanitation resolving the water-energy nexus. Additionally, biogas strongly impacts climate action due to the reduced carbon and greenhouse gas emissions, as most carbon emitted is part of the short-time carbon cycle. This work presented a preliminary and qualitative assessment for such contributions; however, a more detailed and quantitative assessment will greatly benefit.

Biogas production from biomaterial, specifically waste, such as agricultural and municipal waste, is a promising renewable energy source. The main advantages of biogas production are the wide availability and low cost of feedstock, process simplicity, and being an effective waste management tool. The current work has explored the role and contribution of biogas production towards the achievement of different SDGs, set by the United Nations in 2015 as an ambitious plan for the prosperity of humankind and nourishment of the planet. Biogas production has been found to directly impact and contribute to most of the SDGs. The analysis shows biogas would assist in the achievement of the SDGs by:

- Increasing renewable energy production (SDG 7: Affordable and clean energy).
- Reducing climate change impacts (SDG 13: Climate action).
- Reducing air and water pollution (SDG 3: Good health and well-being, SDG 14: Life below water, SDG 15: Life on land).
- Improving agriculture productivity and reducing land-use change (SDG 2: Zero hunger and SDG 15: Life on land).
- Enhancing the waste management process (SDG 11: Sustainable cities and communities, SDG 12: Responsible consumption and production).
- Creating jobs, improving economic development, and adding value to products (SDG 9: Industry, innovation and infrastructure, and SDG 8: Decent work and economic growth).
- Treating wastewater (SDG 6: Clean water and sanitation).

6.1. Implications for practice

The implications for the practice of this work are summarized as follow:

(1) The importance for individuals: The main aim of SDGs is to leave no one behind [252]. To do so, complete utilization of the different technologies is highly recommended; in the current case, biogas. The analysis and linkage that have been delivered in this paper demonstrate how biogas would help that aim (leaving no one behind). The findings show that the direct implication of practice of biogas, for the individual, has the ability to reduce poverty and provide energy for small-scale industrial and rural areas. By providing this linkage, the individual would realize the benefits from it. Moreover, if the different players in the industry adopted the proposed indicators, the individual would be able to get better benefits to form the biogas.

(2) The importance for decision and policymakers: The SDGs' status varies from one country to another [253]. As such, each country would prioritize working towards certain SDGs. As shown in this paper, there is clear evidence that biogas has a significant positive impact on SDGs. In some cases, the impact might be negative. By linking biogas to the SDGs, decision-makers will be able to fully utilize the biogas to assist in achieving the targeted SDGs. Moreover, they can utilize this discussion after ensuring that biogas contribution is maximized and the side effects of the biogas are lowered. The proposed indicators will work as a guideline for them and allow them to benchmark the sustainability performance of the biogas.

(3) The importance of scientific communities: With regards to scientific communities, through highlighting the possible trade-off between biogas and SDGs, and by explaining the limitations of the biogas the scientific communities, we will be able to recognize which research areas could be tackled to improve the biogas sustainability. Additionally, the quantitative relationship between the proposed indicators and biogas has opened a new area of research.

7. Resource recovery and circular economy

The circular economy is defined as the sustainable production and conversion of biomass for a range of food, health, fiber, industrial products, and energy. Renewable biomass encompasses any biological material to be used as raw material [254–256]. The possible role that a circular economy could play in achieving the SDGs can be noticed from the definition. The link can be determined by looking at the possible benefits of the circular economy and linking these benefits to the biogas advantages, as shown in Table 6.

8. Limitations and future research directions

- Although domestic digesters are widely used in countries such as China “the second biogas producer after Germany” and with around 40 million digesters in 2017, gas leakage is one of the main challenges facing domestic bioreactors [270]. The following can be done to minimize such gas leakages, and thus make the biogas industry promising. Preparing educated farmers, providing a biogas storage bag made of flexible fabrics, insulating the top of the digester in winter times, and even providing flares are all different methods that could minimize gas leakage and thus improve the benefits of biogas [129].
- Applying artificial intelligence: the process of biogas production could optimize the biogas reactor's operating conditions, which could lead to increasing the biogas yield and improving the economics of the process [271].
- Novel design of the digester is required to increase efficiency and reduce gas leakage. Allowing the usage of available renewable energy sources, such as solar energy, is required to increase the digester's overall efficiency.
- The production of higher value-added products of the digestate compared to the conventional organic fertilizer, even in smaller amounts but with higher value, would improve the economics of the biogas process [255]. Bionutrients from the digestate would improve the economics of the biogas process. For instance, Khoshnevisan et al. reported the possible preparation of microbial proteins from the digestate [272], biochemical, such as volatile fatty acids [273,274].
- Due to the interrelationship between the SDGs, trade-off, and synergy place many challenges in front of different players in the industry. As such, decision-makers should note that the contribution of biogas towards the achievement of SDGs should be maximized and possible trade-offs between the SDGs minimized. Artificial intelligence and modern technology, known as the Internet of Things (IoT), can determine the relationship between biogas and SDGs. The proposed indicators can be used to increase the biogas contribution to the SDGs. It will also be interesting to see the interrelationship between the proposed indicators. It is recommended that further research be undertaken to determine the linkage of biogas to the SDGs using quantitative methods. Finally, to increase the contribution of SDGs, future research should ensure that biogas:

(1) Increases the total energy produced (SDG 7: affordable and clean energy).
(2) Reduces air and water pollution (SDG 3: good health and well-being, SDG 14: life below water, SDG 15: life on land).
(3) Improves agriculture productivity and reducing land-use change (SDG 2: zero hunger and SDG 15: life on land).
(4) Enhances the waste management (SDG 11: sustainable cities and communities, SDG 12: responsible consumption and production).
(5) Increases the total wastewater treat (SDG 6: clean water and sanitation).
(6) Reduces the methane impact (SDG 3: good health and well-being, SDG 14: life below water, SDG 15: life on land).
(7) Improves the current technology (SDG 2: zero hunger and SDG 15: life on land).
(8) Decreases the impact Impurities (SDG 3: good health and well-being, SDG 14: life below water, SDG 15: life on land).
(9) Reduces operating temperature sensitivity (SDG 11: sustainable cities and communities, SDG 12: responsible consumption and production).
(10) Lowers the sensitivity to the composition (SDG 11: sustainable cities and communities, SDG 12: responsible consumption and production).

- The points mentioned above are applicable for developing countries, mainly since most of the developing countries are still facing challenges in most of the SDGs [275]. As such, any improvement will lead to enhancement of the SDGs status. Moreover, decision-makers will determine the most related barriers by providing a linkage of the biogas barriers with the SDGs and ranking them based on the economic status. To overcome these barriers, stakeholders can use the provided guidelines and indicators in the current study and policymakers in developing countries.

9. Conclusions

Biogas is one of the promising renewable energy sources that can effectively reduce the environmental impact of fossil fuels. The productivity, impurities, and the content of the biogas directly affected

Table 6
Bioeconomy benefits, biogas benefits, and the related SDGs.

Bioeconomy benefits	Biogas benefits	Related SDGs	Refs.
Enhancing the value of materials	Reducing materials carbon footprint	SDG 9: industry, innovation, and infrastructure	[257,258]
Decreasing the dependence on fossil recourse	Reduce climate change impacts	SDG 13: climate action	[259,260]
Improving the resources management	Enhancing the waste management process	SDG 12: responsible consumption and production SDG 15: life on land	[261,262]
Improve food security	Improve agriculture productivity	SDG 2: zero hunger	[263–266]
Reducing CO2 emission per unit of value-added	Reducing air and water pollution	SDG 9: industry, innovation and infrastructure	[255,267]
Providing a broad spectrum of new jobs	Creating jobs	SDG 1: no poverty SDG 8: decent work and economic growth	[268,269]

by the raw materials used for its production. Biogas has several advantages compared to the natural gas. Therefore, it is currently used in several applications starting from small scale in households to large scale in several industries, including power plants.

An extensive analysis was conducted to determine the role of the biogas in achiving the different SDGs. The major contribution comes from increasing renewable energy production (SDG 7); reducing climate change impacts (SDG 13); pollution prevention (SDG 3, SDG 14, and SDG 15); improving agriculture productivity, and reducing land-use change (SDG 2 and SDG 15); enhance waste management (SDG 11 and SDG 12); create jobs, improve economic, and add value to products (SDG 9 and SDG 8); and treat wastewater (SDG 6). Moreover, the technical, economic, and environmental challenges associated with biogas were discussed and connected with the SDGs in developed and developing countries.

A total of 58 indicators have been provided within this work as guidelines for the decision makers and policymakers. The proposed indicators will also reduce the possible trade-off of the biogas into SDGs and will overcome most of the barriers linked to related SDGs. Moreover, the linkage between biogas, circular economy, and SDGs was provided. The results demonstrate that biogas would support the movement towards the circular economy.

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.

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