JAEHR
Journal of Advances in Environmental Health Research
J Adv Environ Health Res. 2025;13(2):68-89. doi: 10.34172/jaehr.1388
http://jaehr.muk.ac.ir

Review Article

Biomass Resource Management and Increasing the Yield of Biogas Production in the Farm: A Review

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Article history:
Received: July 2, 2024
Revised: November 3, 2024
Accepted: November 20, 2024
ePublished: April 20, 2025

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Abstract

Anaerobic digestion (AD) converts animal and agricultural waste into biogas, offering significant benefits for waste management and renewable energy production. It enhances energy security, reduces dependence on imports, and mitigates greenhouse gas emissions. Despite its potential, AD faces challenges that require improved policies, investments, and training. Technological advancements, such as nanotechnology, can further increase biogas production, while by-products like biofertilizer contribute to farm profitability. However, pathogens in animal waste (AW), such as *Escherichia coli* and *Salmonella*, pose public health risks through contamination of water, food, and surfaces. Efficient management of livestock waste is essential to reduce environmental impacts, and the proper pricing of natural resources, including land, water, and landfills, is crucial for sustainability. The benefits of biogas include energy generation, waste reduction, pathogen elimination, and the conversion of organic waste into high-quality fertilizer, which supports agricultural productivity. However, challenges remain, such as small-scale technology, impurities, temperature sensitivity, and limited applicability in urban areas. To improve economic feasibility, the fermentation process can be conducted in controlled environments using digestion tanks. This study explores strategies for effective biomass resource management, focusing on optimizing biogas production and its by-product utilization for sustainable energy development.

Keywords: Animal wastes, Anaerobic digestion, Production potential, Farm profitability, Biogas

Please cite this article as follows: Pirmoghani A, Mohammadrezaei R, Shahmoradi B. Biomass resource management and increasing the yield of biogas production in the farm: a review. J Adv Environ Health Res. 2025; 13(2):68-89. doi:10.34172/jaehr.1388

Introduction

The emission of greenhouse gases (GHGs) and the resulting global warming necessitate the transition to renewable energy sources as an alternative to fossil fuels.[1] In such a situation, it is essential for researchers to explore innovative technologies for sustainable development through the production of bioenergy and biofuels to meet energy demands.[2] Biogas is a methane-rich gas with a very low carbon footprint that is produced through anaerobic digestion (AD) of biological waste.[3] AD is a complex multi-step process, in which organic compounds are finally decomposed into methane and carbon dioxide (CO_2) by the activity of various groups of anaerobic bacteria.[4] In recent decades, its importance has grown significantly.[5] AD was primarily used, but there has been a positive shift toward digesting livestock waste, farm residues, and, more recently, renewable agricultural resources such as energy crops for biogas production.[6] Moreover, biological waste and animal by-products (materials of animal origin) are commonly used as raw materials in biogas power plants.[7] Furthermore, due to limitations in electricity and fuel supplies in remote rural areas, renewable energy sources such as biogas, wave energy, wind energy, and solar energy can play a significant role.[8] On the other hand, rural areas possess abundant biofuel resources, including animal waste (AW), manure, straw, and agricultural residues. Proper utilization of these materials, particularly for biogas production, can supply essential energy to villagers and farms.[9] The increasing focus on developing and implementing new technologies and management methods for handling AWs is a result of global advancements in animal husbandry and increased specialization in agriculture.[10] Transforming these wastes into energy through methods like recycling and AD can deal with a noticeable portion of these issues.[11] In general, improper management of biomass resources poses environmental challenges, acting as a source of air pollution and threatening underground aquifers and surface waters,[12] the utilization of renewable energy can play an important role in reducing environmental damage.[13] In this regard, increasing the efficiency of biogas production in the field is particularly important.[14] In particular, the biogas slurry (biogas slurry/bioslurry BGS), which is a valuable by-product of AD, can be used as vermicompost.[15] Suthar showed that the final carbon to total nitrogen (C:N) ratio (vermicompost) was within the acceptable agricultural range. Therefore, implementing vermicompost technology to convert biogas digester output into compost can reduce fertilizer production costs and enhance soil fertility.[16] Thus, developing new technologies and management methods for utilizing renewable resources has become increasingly necessary, as these resources serve as valuable nutrient sources in agricultural production and play a crucial role in energy generation.[17]

Materials and Methods

In this review, we used keywords such as "livestock waste," "farm profitability," and "anaerobic co-digestion" to identify relevant papers published between 1982 and 2025 in the Google Scholar and PubMed databases. After locating pertinent studies, we first screened the titles and abstracts, followed by a detailed review of the full texts. Additionally, we utilized VOSviewer software to visualize and analyze bibliometric networks. The bibliometric parameters assessed with VOSviewer enabled us to identify key citations related to the primary research topics based on established criteria. Our analysis highlighted the livestock production sector as a key area for development, with a focus on enhancing productivity, profitability, sustainable development, and soil fertility (Figures 1 and 2). VOSviewer has been widely applied in various studies for article evaluation and data visualization. As a result, we extracted and cited 192 papers in this review.

The main objectives of AD can be stated as follows:

1. Waste reuse: Achieve a stable and safe final product by reducing organic content and concentrations of pathogenic agents.
2. Biogas production: Generate biogas as a renewable energy source, adding value to the process.
3. Production of rich fertilizer: Produce nutrient-rich fertilizer suitable for agricultural use due to the reduction of pathogens.

Biogas Composition

Biogas is the result of AD and decomposition of organic matter by microbial activity in the absence of oxygen, which includes a mixture of methane (CH_4), CO_2, and some rare gases. The general composition of biogas is shown in Table 1.

Historical Development

In 1776, Alessandro Volta concluded that there is a direct relationship between the amount of decaying organic matter and the volume of flammable gas produced.[19] In 1859, the first anaerobic fermentation unit was built in India.[20] Some researchers in the 1930s identified anaerobic bacteria and the conditions that cause CH_4 production.[21] The first biogas power plants were designed in the 1970s by some Danish farmers and research centers.[22] Following

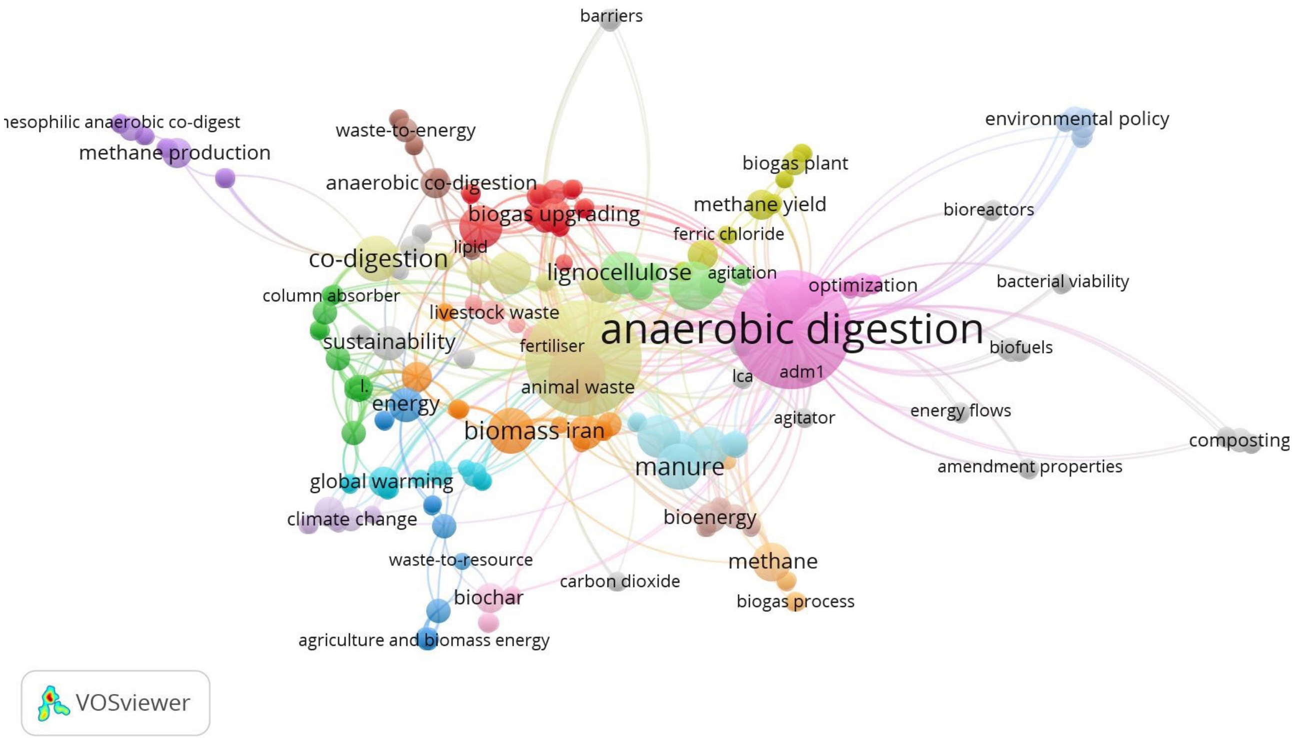

Figure 1. Network Visualization of the Keywords Related to the Biomass Resource Management

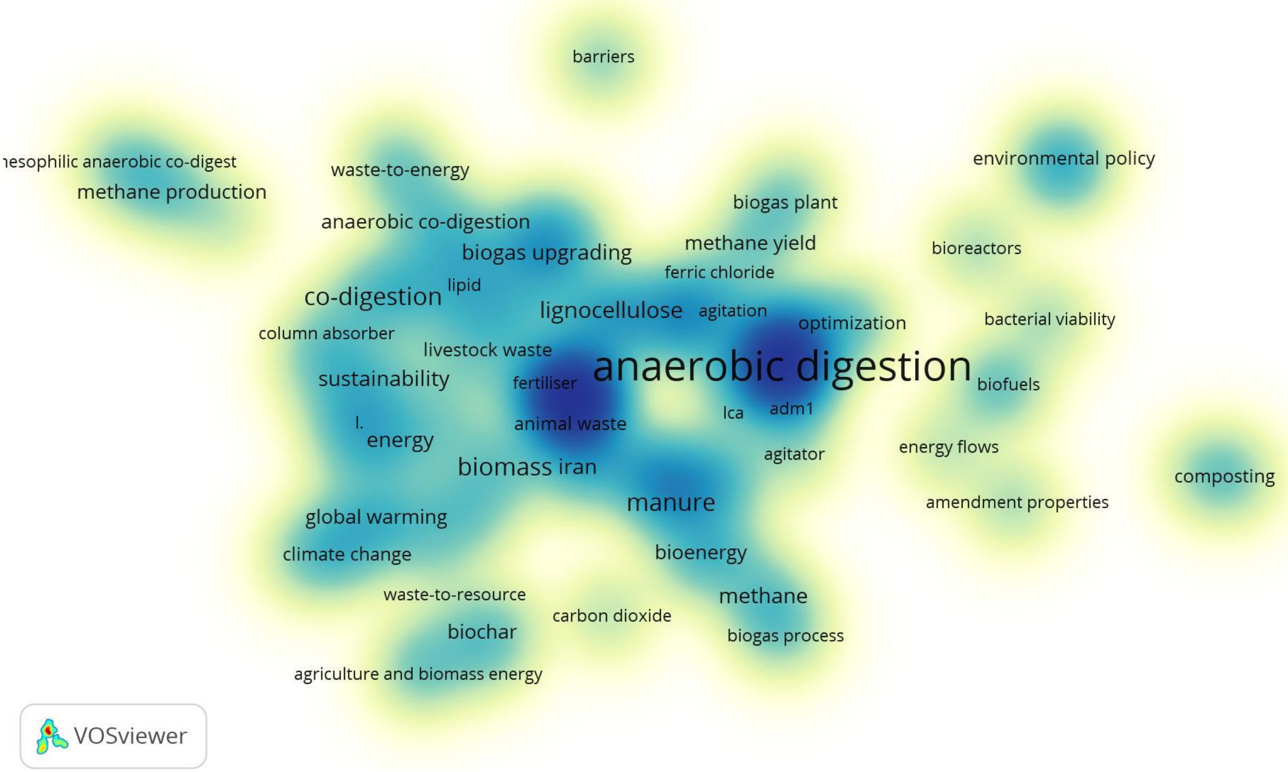

Figure 2. Density Visualization of the Keywords Related to the Biomass Resource Management

Table 1. General Composition of Biogas[18]

Composition of Biogas (%)	Biogas Component
CH_4	45-65
CO_2	30-40
H_2O	0-10
NH_3	0-1
H_2S	0.2-3
N_2	0-5
O_2	0-2

the energy crisis of 1975, biogas plants were considered a cost-effective energy source, leading to the construction of the first large-scale biogas plant in 1974, which was fed with animal and pig waste.[23] Historical evidence also suggests that the use of biogas has a long history in Iran.[24]

Microbiological Stages

The microbiological process involved in biogas production is highly complex, requiring the activation of various microorganisms essential to the AD process. These microorganisms function in close cooperation, and any disruption in their activity can lead to a decline in biogas production or, in the worst case, a complete process failure. Therefore, effective management of biogas production necessitates a comprehensive understanding of the microbial dynamics and functional mechanisms of the microorganisms involved.[25] The AD process occurs in four distinct stages:

- Hydrolysis – Complex organic substances (polymers) such as carbohydrates, fats, nucleic acids, and proteins are broken down into simpler monomer units.
- Acidogenesis – Acid-forming bacteria, leading to the formation of organic acids, further break down the organic compounds produced during hydrolysis. Fermenting bacteria convert sugars and other monomeric organic products into organic acids, alcohols, volatile fatty acids (VFAs), CO_2, hydrogen (H_2), and ammonia (NH_3).
- Acetogenesis – The products of the fermentation phase (organic acids, alcohols) that cannot be directly converted into CH_4 are transformed into CH_4 precursors. VFAs and alcohols are converted into CO_2 and acetic acid (CH_3COOH), which acts as substrates for methanogenic microorganisms in the next stage.
- Methanogenesis – Methanogenic bacteria, which are strict anaerobes, convert CH_3COOH, CO_2, and H_2 into a mixture of CH_4, CO_2, N_2, hydrogen sulfide (H_2S), and other trace gases (Figure 3).

Operational Factors

Several factors influencing digester performance have been investigated. In general, parameters such as digester temperature, residence time, pH, VFAs, NH_3 levels, and stirring speed significantly influence the AD of raw materials (Figure 4) and heavy metals (Ca, K, Mg, Ni, Na) at high concentrations, inhibit gas production and slow down or completely halt the growth of methanogenic bacteria.

Other inhibitory factors, such as toxins, and heavy metals (Ca, K, Mg, Ni, Na) at high concentrations, inhibit

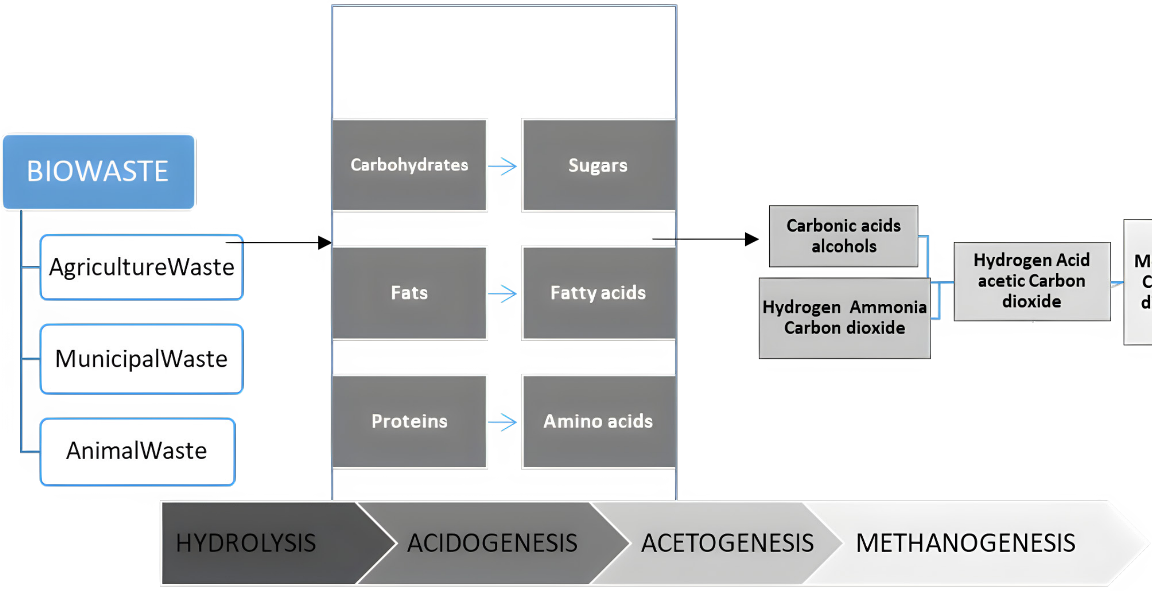

Figure 3. AD Process for Biogas Production

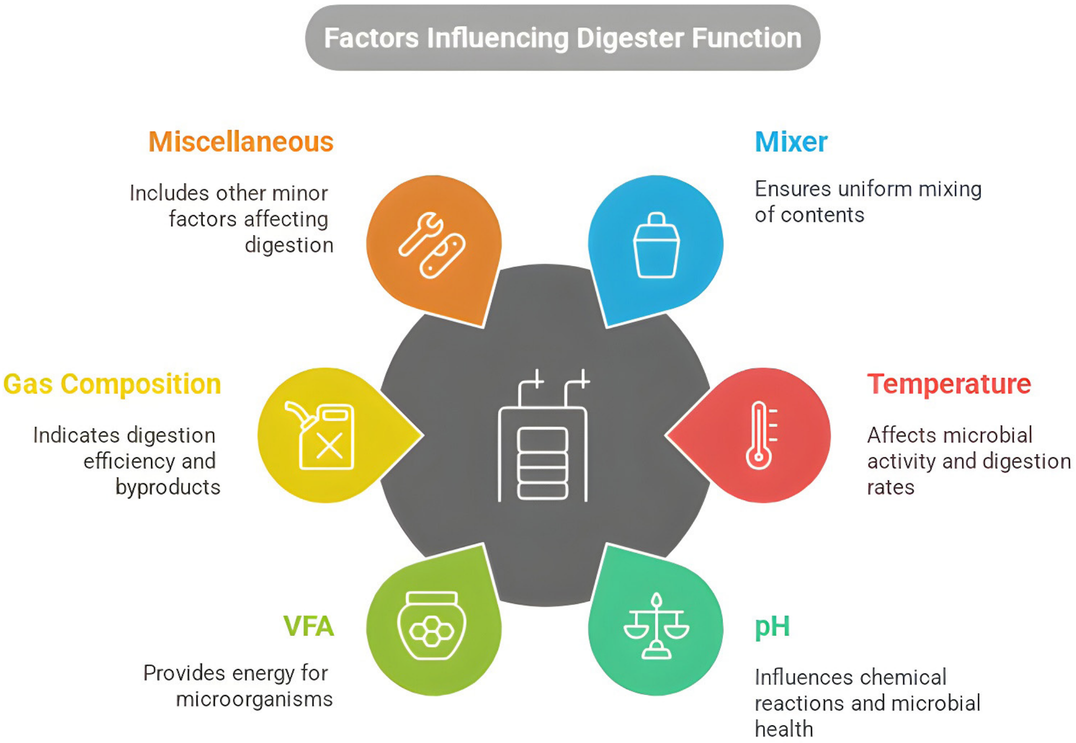

Figure 4. Illustration of Factors Affecting Digester Function

gas production and slow down or completely halt the growth of methanogenic bacteria.[26]

Temperature

Like all biological processes, AD is highly sensitive to temperature, and fluctuations can negatively affect biogas production. At temperatures above 70 °C, the bacterial population becomes inactive, making it crucial to maintain a stable temperature throughout the digestion process. Thermophilic processes are particularly susceptible to temperature fluctuations, whereas mesophilic bacteria can tolerate variations of ± 3 °C without a significant decline in CH_4 production. The optimal temperature range for bacterial activity can be determined based on its effectiveness in sustaining microbial populations.[27]

pH

The pH value of the AD reactor plays a crucial role in the growth of methane-producing microorganisms and influences the decomposition of key compounds such as NH_3, sulfide, and organic acids. Studies have indicated that methanogenic bacteria are most active within a pH range of 6.5–7.2, whereas other fermentative bacteria can function across a broader pH range of 4.0–8.5.[28]

NH_3

NH_3 is a key compound in the AD process and serves as an essential nutrient. It is also a precursor for fertilizer production, with proteins being the primary source of NH_3 in AD. However, excessive NH_3 concentrations inside the digester, particularly free NH_3 (the unionized form), can inhibit the processs.[29] NH_3 concentration is directly related to temperature, meaning the risk of NH_3 inhibition is higher in thermophilic AD processes than in mesophilic ones.

Volatile Fatty Acids

VFAs are the intermediate compounds of acetate, propionate, butyrate, and lactate, which are produced during the acidogenic process with a carbon chain higher than six atoms.[30] Accumulation of long-chain fatty acids may inhibit AD because they are toxic to the two main groups involved in the decomposition of substances, i.e., acetogenins and methanogens. In most cases, instability in the AD process leads to VFA accumulation inside the digester, which may cause a pH decrease. However, VFA accumulation does not always indicate a reduction in pH.[31]

Operation Conditions

Mixing enhances bacterial contact with fermenting materials, thereby increasing the reaction rate. It also prevents the formation of a hard layer on the digested material, which can obstruct gas release.[32] In AD systems, mixing is performed manually on a small scale and mechanically on a large scale. Depending on the rotation speed, mechanical mixers can operate continuously or intermittently throughout the day.

Mixing Purposes

Mixing is the process of combining raw materials, defined as reducing heterogeneity to achieve a desired process outcome. Heterogeneity can refer to variations in concentration, phase, or temperature. In addition, secondary effects such as mass transfer, reactivity, and product properties are often key objectives. In anaerobic digesters, mixing is essential for bacterial activity in biomass and food sources, as it helps stabilize the sludge inside the digester.[33] A sudden increase in temperature or concentration within the digester can have harmful effects on its microbiological community. Another purpose of mixing is to minimize the formation of hard layers and slag in the reactor, ensuring maximum active volume inside the system.[34] When designing a mixing system for a digester, a wide range of variables must be considered, including digester shape, mixing technology, operating time, mixing energy, and sludge rheology. Temperature, solid concentration, biological loading, and pre-digestion sludge treatment influence these factors.

Intensity of Mixing

Mixing during reactor start-up influences the balance between hydrolysis/fermentation and methanogenesis, leading to the accumulation of VFAs and hindering the digestion process. High mixing intensity can negatively affect biogas production during start-up. It also increases the concentration of VFAs, and this instability becomes more pronounced at higher loading rates.[35]

Mixing Methods

Mixing in biogas reactors is crucial as it regulates the digester's environmental conditions by facilitating mass transfer of nutrients and microorganisms, as well as heat transfer. Mixing can be achieved through three methods: hydraulic stirring, mechanical stirring (propellers), and biogas recycling. Natural mixing occurs due to the rise of gas bubbles and heat transfer within the reactor; however, this level of mixing is insufficient to maintain optimal conditions for anaerobic fermentation at high loading rates. Therefore, a dedicated mixing system is necessary to create a homogeneous environment inside the reactor, ensuring full utilization of its volume.[36] Hydraulic agitators typically operate using mechanical pumps installed outside the digester, which move the sludge within the digester and re-inject it at a different location.[37] Gas mixing systems are categorized as either enclosed or unenclosed. In unenclosed systems, biogas is collected at the top of the digester, compressed, and released toward the bottom. As the gas bubbles rise, the displacement of sludge induces mixing. In enclosed systems, biogas is similarly collected and compressed but discharged through a network of pipes. The upward movement of sludge within these pipes generates convection currents, promoting mixing inside the digester.[38]

Impact of Mixing Methods

Karim et al investigated the mixing of enclosed gas in a laboratory-scale digester with a volume of 3.73 liters at different biogas return rates and varying heights of directing pipes.[39] The digester was maintained at a temperature of 35 ± 2 °C and was fed with animal manure (AM) containing 5% solids every two days to achieve a hydraulic retention time (HRT) of 16.2 days. The gas produced in the digester was collected in a tank and recirculated to ensure adequate mixing. The digester was tested at gas recirculation rates of 0, 1, 2, and 3 L/min through directing pipes positioned 40 mm above the tank floor, as well as at a rate of 1 liter per minute through pipes positioned at 13, 26, and 40 mm above the tank floor. After the initial start-up, the material was retained in the digester for 20–30 days. Regardless of the mixing speed, all digesters produced biogas at a rate of 0.40–0.45 L/d, with approximately 65% CH_4 content. No accumulation of fatty acids was observed, indicating a stable digestion process. Additionally, the position of the directing pipes relative to the tank bottom had no impact on biogas production. From these findings, the researchers concluded that mixing conditions did not affect biogas production. This result aligns with the findings of Kaparaju et al but contradicts those of Gómez et al.[40,41] However, without detailed information on sludge rheology or attempts to visualize flow patterns within the digester, the validity of these conclusions cannot be fully verified.

Impact of Feed and Intensity of Mixing

The design and configuration of mixing systems vary and can be either continuous or intermittent. Mixing can also differ in duration and intensity. Research has shown that the intensity and mode of mixing directly affect AD and biogas production.[42] Reducing mixing intensity from continuous to intermittent can enhance biogas production, improve the stability of AD processes, and lower energy consumption associated with mixing. Stafford[43] observed that the concentration of propionic acid in digesters fed with sewage sludge increased shortly after feeding, particularly when lactic acid was added as a feed additive. Additionally, acetate concentrations of up to 4000 mg/L did not inhibit biogas production. Most studies on anaerobic digester mixing have focused on manure slurry or the co-digestion of sewage sludge with municipal waste, incorporating varying fractions of fruit and vegetable waste. Hashimoto and Ong et al obtained similar biogas production results in both continuous and intermittent mixing modes.[44,45] However, biogas production was higher in intermittent mixing mode, particularly with shorter mixing periods. Optimizing the AD process is not solely about increasing CH_4 yield; reducing maintenance and operational costs, such as energy consumption, is also a key factor. Since mixing energy consumption in a full-scale digester can account for 29%–54% of the total energy use in a biogas plant,[46] optimizing mixing can lead to significant energy savings. In co-digestion biogas plants, the substrate preparation stage often represents a larger portion of total energy consumption. However, mixing alone can be responsible for up to 23% of the total electrical energy consumption in a biogas plant.[47] A review of various studies conducted at different scales, using different substrates and mixing regimes, is summarized in Table 2. The findings indicate that intermittent mixing can enhance biogas production and improve process stability compared to continuous mixing. Even if intermittent mixing occurs for only a short period each day, it performs better than systems without an agitator.

Parameters Affecting the Mixing Process

The key parameters influencing the mixing process include the mixing regime and intensity, duration of mixing, blade position, and the geometrical shape of the blade. The previous sections have discussed the mixing regime and intensity, while the following sections will address the remaining factors. A comparison of the effects of different mixing regimes will be presented next:

Table 2. Comparison of the Effects of Different Mixing Regimes

	Mixing intensity					Mixing period		Reference
Feed	**Continuous**	**Without Mixing**	**Periodic**	**High**	**Low**	**Short**	**Long**	
A	1	0	-	-	-	-	-	48
A	0	-	1	-	-	-	-	49
A	0	-	1	-	-	-	-	40
A	0X	-	1Y	0	1	1	0	40
B	0	-	1	-	-	-	-	50
C	-	0	0X	-	-	1	0	51
A	X	-	-	0	0	-	-	35
A	1	0	-	-	-	-	-	39
A	0X	0	-	0	0	-	-	32
A	0X	-	-	0	0	-	-	45
D	0	-	0	-	-	-	-	52
E	1	0	1	-	-	-	-	53
F	-	0	-	0	0	1	0	54
G	0X	1	1XY	0	1	-	-	55
H	1X	0	-	1	0	-	-	55
I	X	-	-	1	0	-	-	56
J	0	-	0X	-	-		0	57
K	0	-	0	-	-		-	58

Note: In these studies, the number zero represents the unfavorable outcome of mixing at the start of the experiment, while the number one indicates an improvement in mixing at the beginning of the study. 'X' denotes different mixing intensities, and 'Y' represents the mixing periods compared in these experiments. Various feeds were used, including **A:** Cow manure; **B:** Primary sludge and activated sludge waste; **C:** Palm oil factory effluent; **D:** Dog food; **E:** A mixture of enriched fat and corn silage; **F:** Initial stages of potato processing; **G:** Olive mill wastewater; **H:** Fermented olive mill wastewater (using fungi); **I:** Rice straw; **J:** Corn silage and a mixture of corn wood and cow manure; **K**: Urban solid waste and organic materials

Mixing Time

Mixing time refers to the duration during which the reactor contents are agitated, playing a crucial role in achieving substrate uniformity. A longer mixing time enhances mass and heat transfer within the reactor. However, it also increases power consumption, which is not always desirable. Understanding mixing time is fundamental for assessing the efficiency of mixing in stirred systems.

Blade Position

To achieve the desired uniformity in stirred tanks, the placement of the impeller must be carefully studied. Optimizing the blade position can reduce both mixing time and power consumption while ensuring uniformity within the tank. Common uniformity levels in previous studies include 90%, 95%, 98%, and 99% of the final concentration. However, the required mixing time varies depending on the chosen uniformity level.[59,60]

Geometric Shape of the Impeller

Understanding the relationship between impeller shape, local flow field characteristics, and overall macroscopic performance is essential for optimizing impeller geometry. Ge et al conducted a hydrodynamic comparison based on Reynolds numbers and concluded that modifying the blade shape to an inclined turbine blade increases radial velocity near the impeller and enhances axial velocity in the central region of the tank.[61]

Biogas Generation at Different Stirring Intensities

The poor performance of many biogas plants can often be attributed to ineffective agitation strategies. Agitation in anaerobic digesters plays a crucial role in evenly distributing the substrate, preventing the formation of floating and settling layers, and enhancing contact between microorganisms and the substrate. However, the intensity and frequency of agitation can have varying effects on biogas production and CH_4 composition. Studies on the impact of different agitation intervals on biogas production have shown that excessive agitation can lead to microbial dispersion, reducing the efficiency of anaerobic fermentation. Conversely, insufficient agitation can cause non-uniformity in the digester bed, slowing down hydrolysis and fermentation rates.[62,63] Therefore, optimizing agitation timing can significantly influence the biogas production rate and the CH_4 content of the exhaust gas. Mohammadrezaei et al observed that in daily biogas production graphs with different mixing rates, as well as in cumulative production graphs across four mixing intensities, the biogas production rate followed a distinct trend. It increased until the fourth day, corresponding to the hydrolysis stage of AD, then slowed down until the eighth day before rising again. Maximum biogas production was observed on the 14th day, after which production began to decline toward zero.[64] This trend was consistent for stirrer rates of 0, 40, and 80 revolutions per minute (rpm). However, at 120 rpm, intensified mixing altered this pattern. At this higher rate, biogas production increased until the fifth day due to enhanced mixing and improved mass and heat transfer. As the process advanced into the acetogenesis and methanogenesis stages, biogas production declined, likely due to the adverse effects of excessive mixing on microbial communities. Lindmark et al conducted a study evaluating the effect of different mixing regimes on biogas production. They examined three scenarios: continuous mixing at 150 rpm, continuous mixing at 25 rpm, and intermittent mixing at minimum intensity during the digestion of fresh municipal organic solid waste.[65]

The results showed that reducing mixing intensity led to an increase in both the biogas production rate and total biogas yield. Notably, continuous mixing at 25 rpm and intermittent mixing at minimal intensity produced similar amounts of biogas after process stabilization, whereas continuous mixing at 150 rpm resulted in reduced biogas production. This decline could not be attributed to VFA inhibition, highlighting the significant influence of fluid dynamics on process performance. Beyond increasing biogas production, optimizing the mixing regime can improve the overall energy efficiency of the AD process. Analysis of cumulative biogas production over 31 days revealed that, during fresh feed digestion, biogas yields were 295.2 ± 2.9, 317.1 ± 1.9, and 304.2 ± 2.8 N mL/g volatile solids (VS) added for mixing at 150 rpm, 25 rpm, and minimal intensity, respectively. During the post-stabilization phase, biogas yields were 113 ± 1.3, 134 ± 1.1, and 130 ± 1.0 N mL/g VS added for the same mixing regimes. These findings suggest that reducing mixing intensity, particularly within an optimal range, can enhance biogas production, maintain process stability, and lower energy costs associated with agitation. Optimizing mixing strategies can contribute to improved anaerobic digester design and operation, ultimately supporting the development of more efficient biogas systems in the waste management industry.

Hydraulic Residence Time of the Mixture

The HRT refers to the duration between the entry of material into the digester tank and its exit. It is determined by the volume of the digester and the feed material volume per unit of time.[66] HRT varies depending on climatic conditions, with differences observed between tropical and colder regions. It must be sufficient to ensure that the number of microorganisms removed does not exceed the number being produced. Additionally, HRT is influenced by the decomposition rate of the input materials and the temperature at which the fermentation process occurs.

Pretreatment

Biological waste originates from agriculture, food processing industries, AM, and municipal waste. It includes complex carbohydrate polymers (cellulose and hemicellulose), aromatic polymers (lignin), proteins, and lipids. The pretreatment method required for biological waste depends on its composition. Lignocellulosic biomass, such as cereal straw, sugarcane bagasse, and agricultural residues, consists of lignin, hemicellulose, and cellulose, making it a viable raw material for biofuel production. However, this type of biomass is resistant in nature, and microorganisms are not able to consume it. Therefore, pretreatment methods-physical, chemical, or biological-are necessary to hydrolyze the biomass and release free sugars. Other pretreatment techniques, such as deep eutectic solvents (DES), have also been explored.[67] In addition, methods for removing salts and inhibitory compounds have been reported. Electrodialysis is commonly used for salt removal, while adsorption using activated carbon is the most effective method for removing metals.[68] Various chemical treatments, including precipitation and oxidation, are also applied to prepare biomass for microbial fermentation.[69]

Discussion

Potential of Using Agricultural Biogas Resources

First-generation biofuels are produced from food crops such as corn, sugarcane, and palm oil and are currently the most widely used in fuel production systems. These feedstocks contain starch or sugar, which can be easily converted into bioethanol through fermentation, or oil, which can be extracted and processed into biodiesel. Common bioethanol feedstocks include sugarcane, sugar beet, corn, and wheat, while biodiesel is primarily derived from soybean, palm oil, rapeseed, and sunflower due to their large-scale production and commercial viability. Crop residues such as wheat straw and corn stalks are considered potential sources for additional energy production alongside primary crop-derived energy. These residues fall under the category of lignocellulosic biomass, which serves as a feedstock for second-generation biofuels. Lignocellulosic biomass is the most abundant renewable resource globally and does not compete with food sources, making it a sustainable alternative. The global share of grain production and crop residues in the United States, Brazil, and the Netherlands averages 2.2% and 2.3%, respectively, while Iran's share stands at 0.86% for grain production and 0.9% for plant residues.[70] Wang et al suggested that biomass from plant residues could provide up to 25% of energy needs.[71] In addition, bioenergy derived from forest residues, wood fibers, byproducts from wood pulp mills, and agricultural waste has significant potential for thermal and electrical energy production, contributing to climate change mitigation in Canada. In Iran, agricultural biomass from residues amounts to approximately 11.33 million tons (Mt), capable of producing 3.84 gigaliters (GL) of bioethanol, 1.07 GL of biobutanol, 3.15 billion m^3 of biogas, and 0.90 billion m^3 of biohydrogen.[72] Germany, due to its agricultural development, has become the world's leading biogas producer. By the end of 2009, around 4000 agricultural biogas production units were operational on German farms.[73]

Potential of Using Animal Waste Biogas Resources

Livestock contributes approximately 40% to the global value of crops and plays a vital role in food security, supporting around 1.3 billion people worldwide.[74] In 2019, global livestock and poultry production included 1.51 billion cattle, 27.54 billion poultry, and 2.33 billion sheep and goats. By 2030, it is projected that an additional 130 million cows, 2.02 billion chickens, and 250 million sheep and goats will be added to global livestock numbers.[75] In Iran, the total number of industrial cattle farms in 2019 was 26 983, with a capacity of 3 670 796 fattening cows and calves. Estimates of Iran's AW potential from 2011 suggest that the country could produce approximately 8600 million cubic meters of biogas from animal waste, with 70% originating from heavy livestock, 23% from poultry, and 7% from light livestock.[76,77] Global meat consumption is expected to rise from 133 million tons in 1980 to 452 million tons by 2050, with 86% (279 million tons) of this increase occurring in developing countries.[78] In this context, bioenergy production from AM is more prevalent in the European Union, where over 5,995 tons of AW are used as raw materials for biofuel across 27 countries[79] (Figure 5). The observations of a research performed in Germany indicates that most biogas power plants are located in regions with intensive animal husbandry. The quality of AW used for biogas production depends on several factors, including the species and age of the animal and its diet (protein and fiber content).[80]

Bioelectricity Energy

The World Bank reported in 2018 that approximately

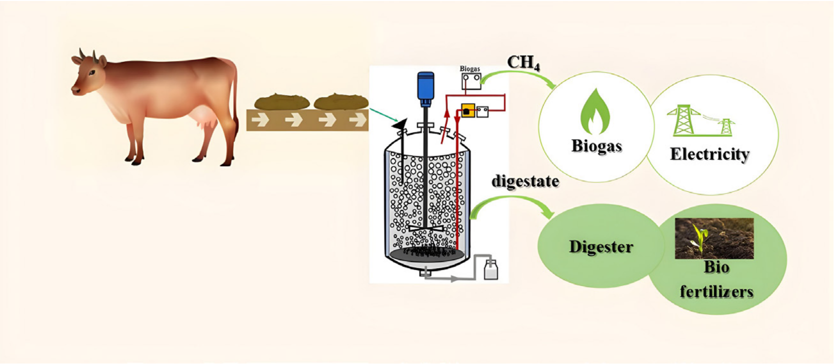

Figure 5. Potential of Using Animal Waste Biogas Resources

724 million people lacked a regular and reliable supply of electrical energy, with 84.2% of them living in rural areas isolated from power grids, while the remaining 15.8% resided in urban areas.[81] Biological waste can serve as a raw material for electricity generation using microbial fuel cells. These bioreactors allow microbes to convert chemical energy into electrical energy by utilizing organic carbon from waste under anaerobic conditions. According to the International Renewable Energy Agency (IRENA), the current global share of renewable energy in electricity generation stands at approximately 25%, varying by region. This share is expected to rise to 85% by 2050.[82] For instance, Abdeshahian et al reported that due to the recent growth in animal husbandry in Malaysia, the potential for biogas production from AW could reach 4.6 million m^3 per year, which could generate up to 8.27×10^9 kWh of electricity annually.[83] Similarly, global biomass electricity production increased from 429 TWh in 2014 to 474 GWh in 2015. In general, electricity generation from biogas has a lower environmental impact compared to fossil fuel-based energy systems. Khalil et al in 2019 investigated biogas production from AW in Indonesia and estimated that approximately 9,597.4 Mm^3 per year of biogas could be produced, which could be used to generate up to 1.7×10^6 kWh of electricity annually.[84]

Warming Bioenergy

Studies have shown that AD is one of the most energy-intensive waste treatment processes in the world. European countries such as Germany, Spain, France, and the Netherlands are among the largest users of AD technology, with a combined total capacity of 7.7 million tons per year of municipal solid waste.[85] Recent biological innovations have focused on promoting biogas production through various strategies.[86] Currently, more than 2.3% of global renewable energy use in the heating sector comes from traditional biomass sources, including firewood, charcoal, AM, and plant residues.[87, 88] Biomass is the most commonly used resource for both cooling and heating, and its share in these sectors is expected to increase from 2.2% in 2005 to 3.8% by 2020.[89] Moreover, by the end of 2018, over 18 000 biogas power plants were operational worldwide.[90] In low-income areas, biogas is primarily used for cooking and heating, significantly reducing indoor pollution.

Biofuel

AD benefits from advantages, including technical ease, flexibility for different scales and types of waste, and relatively low costs compared to other waste-to-energy technologies. As a result, this technology can be easily applied on both large and small scales. Many countries have already adopted AD as a means to implement waste-to-energy technologies for sustainable energy production[91]; the US Renewable Fuel Standards Program predicts that by 2022, approximately 44.5% of the 36 billion gallons of renewable fuel will be produced from cellulosic biofuels, with about 56.9% of that coming from agricultural residues. The remaining share will be from South and Central America, including Brazil (28.7%), Europe and Eurasia, including the Netherlands (16.5%), and the Asia Pacific, including China (10.6%).[92] Biomethane does not require additional investments to develop new infrastructure to replace fossil fuels because existing gas infrastructure is already suitable for biomethane use. This makes it a key solution for providing affordable and renewable energy to consumers. Currently, there are 18 million compressed natural gas (CNG)-driven vehicles worldwide and 22 000 fuel stations with the infrastructure to deliver natural gas as fuel.[93]

Biogas Upgrading

Biological methods have been used for nearly 70 years to purify gases such as odors, H_2S, NH_3, mercaptans, and hydrocarbons.[94] In the 21st century, these methods have gained increasing attention, particularly in gas purification and biogas upgrading, due to their advantages over conventional physicochemical techniques. The key benefits of biological purification include simplicity, low operational costs, and environmental sustainability. The process of upgrading biogas to high-quality biomethane for use as vehicle fuel or injection into natural gas grids is expanding.[95,96] In developing countries, biogas is primarily produced in small domestic digesters, serving as a fuel source for cooking and lighting. In contrast, developed countries focus on large-scale biogas production from farm-based and commercial plants, where the primary applications are electricity and heat generation.[97] Biogas has a calorific value of approximately 600 BTU (151 to 1975 kcal) per cubic foot, which is equivalent to half a liter of diesel fuel. This makes it a viable energy source for heating, cooking, and lighting.[98]

Biofertilizer to Increase Profitability in the Farm

Manure can be used directly as feed for fish or indirectly as a food source for phytoplankton, zooplankton, and zoobenthos, which are then consumed by herbivorous fish.[99] AD is an environmentally friendly technology that effectively recycles waste biomass from agricultural and industrial activities, as well as organic solid waste generated by rural and urban populations. AD can serve as a key component of sustainable development, promoting high productivity and profitability.[100] According to projections, the production cost of AD will decrease by approximately 38% by 2050 compared to 2015.[101] Currently, AD and composting are the two most widely used techniques for AM treatment worldwide, contributing significantly to circular economy goals. A recent study suggests that biogas production via AD is highly beneficial due to its low cost, environmental sustainability, pathogen reduction, and organic fertilizer production as a valuable by-product.[102] Compared to aerobic digestion, AD generates less solid sludge. Additionally, while composting produces only a single product, AD not only generates biogas but also yields a nutrient-rich fertilizer.[103] This biofertilizer contains essential plant nutrients such as phosphorus (P), nitrogen (N), potassium (K), and trace elements, making it an excellent soil conditioner with high cation exchange capacity, porosity, water-holding capacity, and microbial activity. It can replace mineral fertilizers, increasing crop yield and stability. For smallholder farmers who cannot afford mineral fertilizers, livestock manure from AD can serve as an affordable and nutrient-rich alternative. Additionally, the use of AD-derived biofertilizer in greenhouses, organic farming, and mushroom cultivation can generate significant income. BGS is particularly valuable as it contains bioactive compounds that promote soil health, microbial diversity, and nutrient efficiency. Liu et al found that BS enhanced the early and rapid growth of rapeseed, increasing photosynthesis, dry matter accumulation, and nutrient transport capacity.[104] Furthermore, recent research indicates that algae cultivated from AW can be converted into bio-oil and other valuable products, providing economic benefits and job opportunities in rural areas while mitigating the environmental problems caused by improper disposal of animal waste.[105] Also, the N content in fertilizer derived from biogas plants is higher in quality compared to that from conventional methods. Unlike traditional fertilizers, biogas-derived fertilizer is also free from unpleasant odors.

Economic Perspective

The economic evaluation of AD serves as a preliminary guide to assess its economic feasibility, particularly by analyzing CH_4 volatilization during biogas production from food waste. This assessment provides valuable insights for biogas project developers. The livestock and agricultural sectors form a highly competitive industry that not only supports industrial development but also serves as a key driver of economic growth, contributing to high productivity, profitability, food security, and job creation.[106] However, nearly one-third of the food produced within the global food chain is lost as waste, leading to significant economic losses and environmental threats. Implementing waste-to-energy technologies and recovering valuable nutrients can not only enhance economic conditions but also support sustainable societal development.[107] Biogas is a clean fuel that does not contribute to environmental pollution and carries a low risk of explosion. The presence of CO_2 in biogas acts as a fire retardant, reducing flammability. However, excessive CO_2 content lowers its calorific value. By filtering out CO_2, the energy content of biogas can be significantly improved. The CH_4 content of biogas depends on the temperature of the digester—lower temperatures result in higher CH_4 concentrations, increasing calorific value, while higher temperatures lead to greater gas production but lower energy efficiency. By integrating all the benefits of AD systems, GHG emissions can be reduced, and revenue can be increased by at least 80%. As a result, there is growing interest from environmental regulatory agencies and livestock associations in expanding AD technology as a strategy to mitigate GHG emissions.[108,109]

Advancement in Biogas Production

In recent years, several challenges have been identified regarding the efficiency of the AD process. To address these issues, nanoparticles (NPs) have been widely integrated into the AD process to enhance organic waste conversion into biogas and other valuable outputs. This advancement has led to improved microbial growth and metabolic activity.[110] This study underlines that metal NPs, metal nutrient NPs, and iron oxide NPs are more effective in boosting biogas and CH_4 production compared to metal oxide NPs (e.g., CuO, Mn_2O_3, Al2O3, and ZnO).[111] The efficiency of NPs in AD depends significantly on factors such as dosage, feedstock type, feed degradability, pH levels, and NP composition.[112] Studies indicate that reducing the cost of NPs and utilizing low concentrations can lead to a more than 90% increase in biogas production compared to control conditions, making the approach economically viable.[113] Abdelwahab et al reported that Fe NPs at concentrations exceeding 100 mg/L are more effective in reducing H_2S production rather than enhancing CH_4 yield. Meanwhile, Ni NPs and Co NPs at concentrations above 2 mg/L and 1 mg/L, respectively, negatively impact CH_4 production.[114] Furthermore, Eljamal et al found that the addition of zero-valent iron (Fe^0) at an optimal concentration of 10 mg/L, with a dosing time of 12 hours, and a feedstock ratio of aloe vera waste to waste sludge at 2:1, led to a 146.9% increase in CH_4 production.[115] Finally, this review examines the latest advancements in NP applications for biogas production to promote the further development of AD technology. Moreover, biogas system location and size play a crucial role in balancing profitability and environmental impact. Tools such as life cycle assessment and life cycle cost analysis are widely used to evaluate environmental and financial impacts throughout the entire lifespan of the AD process.[116] Life cycle assessment is further integrated with thermodynamic process models, geographic information system (GIS)-based infrastructure design, and uncertainty quantification, to provide stakeholders with economic, environmental, and energy performance insights regarding biogas production systems.[117]

Challenges in Biogas Production

Previous studies have identified several key challenges in the implementation of bioenergy technology, including economic and financial constraints, market and infrastructure limitations, regulatory and administrative barriers, local opposition, site selection issues, and environmental concerns.[118] One of the primary obstacles is the significant initial investment required for biogas facilities. The lack of specific incentives can hinder biogas expansion, leading to both economic and social consequences.[119] Policy and governance also play a crucial role in promoting biogas development. A combination of appropriate political measures and financial incentives can encourage companies to invest in and operate biogas production facilities. For instance, in March 1999, Germany implemented a major tax reform, introducing a tax on energy sources and carbon emissions, while granting tax exemptions for renewable energy sources.[120] Another critical challenge is the limited financial capacity of small-scale farmers, who may lack the capital needed to invest in biogas equipment and infrastructure. Moreover, many individuals who have access to raw materials suitable for biogas production often lack adequate knowledge and technical expertise about biogas technology. Vu et al found that farmers in their study had limited experience in managing liquid manure, composting solid manure, or reducing pollution through microbial processes.[121] Therefore, educating and training rural communities on biogas technology is essential to facilitating its adoption.[122] Okpaga et al observed that farmers can mitigate the environmental impacts of AW by adopting innovative waste management methods, such as vermicomposting, biogas production from waste, membrane filtration, liquid-solid separation, thermal treatment, and chemical treatment.[123] Additionally, a study by Ketuama and Roubík demonstrated that small-scale biogas plants are economically viable. They concluded that providing extension services, financial incentives, and regulatory support for small-scale biogas markets can encourage farmers to adopt this technology.[124] Ultimately, increasing awareness and acceptance of biogas technology is critical for its widespread adoption. Farmers need to recognize its economic and environmental benefits to fully embrace biogas as a sustainable energy source.

Potential Effects of Unmanaged Livestock and Agricultural Wastes

Heavy Metal Contamination

The expansion of livestock breeding by approximately 5% indicates that contamination from livestock waste continues to increase.[125] AW can exist in solid, liquid, or gaseous forms, including animal dung, droppings, discarded feed, feathers, fur, decayed animal carcasses, blood waste, effluent from animal farms, milk waste, and urine.[126] Qi et al reported that cow manure is the most abundantly produced type of AM.[127] This is primarily due to cows having a higher daily feed intake, a greater manure excretion rate, and a more frequent feeding cycle compared to other animals. To enhance economic efficiency, improve feed utilization, and prevent diseases, livestock and poultry farming enterprises often add heavy metal-containing additives to animal feed. Some metals, such as Fe, I, Co, Zn, Cu, Mn, Mo, and Se, are essential for maintaining various physiological functions and are commonly included as feed additives.[128] However, a significant portion of these heavy metals is not utilized by the animals and is excreted through manure and urine. This leads to the introduction of heavy metals into agricultural soils, increasing their concentration in crops and posing environmental and public health risks.[129] Zhen et al found that continuous and high-rate application of AM significantly increased the total concentration of Cd, Zn, Cr, and Cu in the soil. Although AM application contributed to an increase in soil organic matter, excessive use also heightened the bioavailability of heavy metals, exacerbating contamination risks.[130] Moreover, concerns remain regarding the presence of arsenic in grass meal, which requires further attention and monitoring.

Water Pollution

The World Health Organization (WHO) has ranked infectious diseases caused by pathogenic agents-including viruses, bacteria, fungi, and parasites-as the second leading cause of death globally.[131] A major source of both pathogenic and non-pathogenic agents is animal waste, which contains harmful microorganisms such as Escherichia coli and Salmonella, both of which can adapt to various hosts.[132] Animal excrement is typically stored in lagoons adjacent to fields for later use as fertilizer. However, runoff from these storage lagoons can infiltrate surface and groundwater, leading to contamination of water bodies and soil. This runoff carries high concentrations of P, N, and heavy metals such as Pb, Cu, Ni, and Zn, posing serious environmental and health risks.[133] Excessive N and P discharge contributes to the eutrophication of water bodies, triggering algal blooms.[134] The proliferation of cyanobacteria has become increasingly prevalent due to climate change, driven by rising global temperatures and increased nutrient runoff, particularly N and P from agricultural activities.[135] Cyanobacterial blooms not only deteriorate water quality but also produce highly toxic secondary metabolites, posing serious risks to human health and drinking water safety.

Microcystins (MCs) are among the most common algal toxins, characterized by their cyclic heptapeptide structure.[136] Numerous studies have identified different variants of MCs, including MC-LR, MC-RR, and MC-YR, with MC-LR being the most prevalent and extensively studied due to its severe toxicity. As a result of its widespread occurrence and high toxicity, MC-LR is currently regarded as the reference compound for assessing cyanotoxin contamination.[137]

Air Pollution

Growing public awareness of environmental issues and increased concern for quality of life have led to the recognition of odors as harmful air pollutants. Unpleasant odors can trigger various emotional and physiological responses, ranging from mild discomfort to documented health effects, ultimately reducing overall quality of life.[138] Under severe odor exposure, health-related symptoms may occur, while moderate exposure tends to cause annoyance, particularly among residents living near odor sources. In the livestock sector, unpleasant odors primarily originate from the storage of AM. However, they can also arise from animal housing and the application of manure as fertilizer.[139] The expansion of residential areas near farms, along with the intensification and specialization of animal husbandry, has significantly increased the impact of these odors on nearby communities. The primary odorous compounds emitted from farms include NH_3, (H_2S), and volatile organic compounds (VOCs).[140] The experimental data obtained in Haider and colleagues' study provide an inventory reference for both VOCs and their emissions from AM. In addition, it refers to aromatic compounds and VOCs that act as atmospheric aerosol precursors.[141] In addition, Millner reported that workers in animal housing facilities are exposed to high concentrations of volatile compounds (NH_3, CH_4, H_2S, and various organic substances), dust (fine particles, endotoxins, and animal feed residues), and bioaerosols (bacteria, viruses, fungi, parasites, and mycotoxins). all of these parameters can pose significant health risks-particularly for vulnerable populations such as children and the elderly, especially those with asthma.[142] To address these concerns, future research should explore the effectiveness of various AM treatment methods to support sustainable agricultural practices and minimize environmental and health impacts.

Antibiotics

In European countries, the total amount of antibiotics used per kilogram of livestock ranges from less than 20 to 188 mg.[143] After administration, approximately 30% to 90% of antibiotics given to animals are excreted through manure.[144] The misuse and overuse of antibiotics in (*i*) livestock farming for animal growth promotion, (*ii*) human medicine for bacterial infection treatment, and (*iii*) agriculture for crop production have contributed to the emergence and spread of antibiotic-resistant bacteria (ARB).[145] Poindexter and Liu reported that the application of manure as fertilizer increases environmental exposure to antibiotics, ARB, and antibiotic resistance genes (ARGs), which can be transferred to agricultural fields and surrounding ecosystems.[146,147] This has been observed with antibiotics such as sulfamethazine, tetracycline, and chlortetracycline.[148] The fate of these compounds depends on their physicochemical properties and soil composition—some may persist in manure-fertilized soil, while others may leach into groundwater or enter surface water through runoff. Antibiotic residues can be transported over long distances, impacting entire aquatic ecosystems.[149] The persistence of pharmaceutical compounds in the environment, particularly in water and agricultural resources (e.g., vegetable cultivation), poses a significant environmental challenge due to their stability and resistance to degradation.[150] In response to public health concerns, GlobalGAP regulations prohibit the use of untreated AM on leafy vegetables after planting and mandate a 60-day restriction before harvesting for other crops.[151] Therefore, assessing the environmental impact of stored AW runoff is crucial for controlling the evolution of antibiotic resistance under the "One Health" framework.[152] The risk of antibiotic transmission to humans increases with certain consumption habits, such as drinking contaminated water, consuming raw or undercooked food, or failing to observe proper hygiene practices, including adequate handwashing. Tiedje et al reported that agricultural workers face significant health and safety risks due to exposure to antibiotic-contaminated environments and occupational contact with pathogenic agents in food production.[153] Given these concerns, effective management strategies are essential to mitigate antibiotic residue risks and prevent the spread of antibiotic resistance in agricultural settings. In this context, mycotoxins have emerged as one of the most significant natural pollutants, posing serious food safety challenges in both developed and developing countries. Recent studies indicate a continuous increase in the prevalence and concentration of emerging mycotoxins in animal feed and feed ingredients (e.g., cereals and soybeans) worldwide.[154]

Zoonosis

The One Health framework emphasizes the interconnectedness of human, animal, and environmental health. Poor manure management can contribute to the transmission of zoonotic diseases, posing a significant public health risk, particularly in urban and suburban areas where livestock are kept.[155] Harris et al observed that markers of ruminant waste were present on children's hands and household floor sponge samples, even in areas without ruminants, indicating widespread environmental contamination.[156] Free-range grazing is a common livestock practice in many low-income communities, increasing the risk of fecal contamination in households that do not own livestock. Gizaw et al reported that domestic animals and their excreta were not properly managed in their study area, increasing human exposure to AW and raising concerns about associated health risks.[157] When AM is not effectively removed from human living environments, it facilitates fecal-oral transmission of zoonotic pathogens through contaminated hands, food, and water. Studies have linked exposure to AM with intestinal infections, diarrhea, stunted growth, impaired cognitive development, and even mortality in humans.[158] Untreated manure can harbor a wide range of pathogens harmful to human health. The hepatitis E virus (HEV) has been detected in animal waste, sewage, inadequately treated water, shellfish, contaminated agricultural products, and animal meat.[159] Additionally, echinococcosis, a global zoonotic disease caused by *Echinococcus granulosus* (sensu lato) and *Echinococcus multilocularis*, remains a major public health concern.[160] The WHO classifies echinococcosis as one of the 20 neglected tropical diseases, emphasizing its significant global health impact.[161] Disease severity varies based on the size, number, and location of cysts. Humans, as accidental hosts, become infected by ingesting parasite eggs through contaminated food, water, soil, or contact with infected animal fur. While some cases of hydatidosis are asymptomatic, severe infections can be fatal.[162] Christophe et al noted that although existing manure treatment methods partially reduce pathogen loads, promoting more effective interventions-such as biogas production and composting-could significantly enhance public health protection.[163]

Agriculture's Contribution to Climate Change

Agricultural activities, including the cultivation and processing of crops (e.g., fruit and vegetable skins, seeds, sugarcane bagasse, and wood branches), as well as livestock and poultry farming (e.g., urine, feces, waste milk, bedding materials, birth tissues, bones, and blood), are major sources of agricultural waste production.[164] Globally, agricultural waste, which includes by-products from staple food production, fruits, vegetables, and AM, amounts to approximately 998 million tons annually.[165] Traditionally, agricultural waste is burned to prepare land for the next cropping season. However, this practice contributes significantly to climate change. Climate changes driven by human activities are caused by several pollutants, with CO_2, CH_4, and nitrous oxide (N_2O) being the three main GHGs responsible for global warming.[166] Agriculture and food production contribute to the emissions of all three gases, though agriculture's direct emissions are unique in that they are primarily driven by CH_4 and N_2O. For instance, the use of fertilizers and the transportation of crops are major factors in GHG emissions.[167] The environmental concerns associated with agriculture are vast. The production and application of N fertilizers is energy-intensive and accounts for approximately 5% of global GHG emissions.[168] Besides, NH_3 contributes to air pollution and respiratory health issues, while the leaching of nitrate (NO_3^-) and ammonium (NH_4^+) into water bodies leads to acidification, eutrophication, and groundwater contamination.[169] It is estimated that around 50% of the total global NO_3^- entering water sources originates from agricultural activities. N_2O is a particularly potent GHG linked to human activities, with agriculture being its largest source. Given the significant impact of these emissions, it is crucial to explore effective mitigation strategies to reduce their atmospheric concentrations and minimize their long-term environmental consequences.[170,171]

Global Warming

Climate change is widely recognized as one of the most significant health threats of the 21st century. Addressing climate change, therefore, presents a crucial opportunity to improve public health. Over the past century, the average global surface air temperature over both land and oceans has steadily increased, leading to observable environmental changes such as warming oceans, rising sea levels, melting glaciers, and shrinking sea ice. The Intergovernmental Panel on Climate Change (IPCC) has attributed global warming to the increase in GHG emissions resulting from human activities (Table 3). The long-term consequences of climate change are expected to affect human health, marine and terrestrial ecosystems, water resources, and vegetation.[172] Rising sea levels pose a particular threat to low-lying coastal regions, increasing the risk of flooding, reducing arable land, and exacerbating freshwater shortages. According to the WHO, if climate change mitigation strategies are not implemented, an estimated 131 000 additional child deaths per year will occur by 2030 due to climate-related factors.[173] In response to these global challenges, the United Nations (UN) adopted the Sustainable Development Goals (SDGs) in 2015.[174] (Figure 6). This initiative aims to end poverty, protect the planet, and ensure prosperity for all by 2030.[175] Healthier environments could significantly reduce the global burden of disease. In 2016, nearly 13.7 million deaths worldwide-accounting for 24% of total global mortality-were linked to modifiable environmental factors. This statistic highlights that approximately one in four deaths globally is associated with environmental conditions.[176,177]

Enteric CH_4 From Microbial Fermentation and GHG

While transportation and fossil fuel combustion are widely recognized as the primary contributors to GHG emissions and climate change, the livestock sector has also been identified as a significant environmental threat. A 2006 Food and Agriculture Organization (FAO) report highlighted that livestock farming contributes extensively to deforestation, land degradation, soil cultivation, and desertification, all of which are major sources of CO_2 emissions associated with land use in the sector.[101] The global livestock industry relies heavily on feed production, consuming approximately 80% of the world's soybean crops and over 50% of global corn supplies.[178] One of the most critical contributors to GHG emissions within this sector is CH_4, which results from the microbial fermentation of plant material in the digestive systems of ruminant animals, particularly cattle. This process accounts for nearly 30% of global CH_4 emissions, making it the largest direct source of GHG emissions from beef and dairy production.[179] In the United States, enteric fermentation is responsible for approximately 26.7% of total CH_4 emissions, contributing to around 2.7% of human-induced GHG emissions.[180] The production of intestinal CH_4 is influenced by several factors, including animal age, body weight, feed quality, and digestive efficiency.[181] Overall, livestock farming accounts for 35%–40% of annual anthropogenic CH_4

Table 3. Climate Changes and Their Direct and Indirect Effects[177]

Direct Effects	Indirect Effects
Heatwaves	Changes in ecosystems
Severe weather	Impact on health
Drought	Allergic
Flooding	Respiratory diseases

Figure 6. Four Items of SDG Related to Biogas

emissions, underscoring the urgency of mitigating its environmental impact. To prevent further ecological damage, GHG emissions per unit of livestock production must be reduced by at least 50%.[181, 182] In this regard, modulating rumen performance has become a focal strategy for enhancing animal productivity while reducing environmental pollution. The use of plant-based feed additives has gained significant attention as an alternative to antibiotics in animal feed, aligning with sustainable agricultural practices. Over the past few decades, various approaches have been explored to reduce enteric CH_4 emissions, primarily focusing on nutritional strategies, genetic improvements, and optimized animal management practices[183] (Table 4).

Suggestions

The management of biomass resources can be significantly enhanced through innovations in the production of raw biomass materials. This approach aims to increase sustainable biomass production while providing clean energy feedstocks. Achieving these goals involves the modification, cultivation, and harvesting of biomass resources, which will ultimately facilitate the commercialization of advanced clean energy technologies in the coming years.

The innovation process for biomass raw materials can be broken down into two main phases: design and feasibility. The design phase focuses on the conceptualization and implementation of cutting-edge technologies tailored to optimize biomass production. Several innovations can be applied across different biomass feedstocks, including but not limited to breeding and propagation techniques, advanced cultivation and harvesting methods, on-farm processing innovations, and the development of decision support systems.

A wide variety of biomass feedstocks and technological advancements can contribute to more effective biomass resource management. Examples include the cultivation of microalgae, improvements in hemp production, optimizing tree planting efficiency through the use of bio-based tree shelters, and exploring drone-assisted harvesting methods. These advancements, when combined, have the potential to improve the efficiency and sustainability of biomass resource management practices. For different biomass feedstocks, a broad range of innovations have focused on breeding and propagation, cultivation and harvesting, on-farm processing, and decision support systems.

Conclusion

A key takeaway from biomass resource management is that improving the efficiency of livestock waste utilization can significantly reduce environmental impacts. While adjusting the scale of operations, inputs, and waste management can help achieve greater efficiency, a critical element is the correct pricing of natural resources, including land, water, and waste disposal. Often, natural resources are available for free or at low cost, leading to overexploitation and pollution. Unfair subsidies directly encourage livestock producers to engage in

Table 4. Suggestions and Assessments Made Regarding the Reduction and Management of GHG in the Livestock Sector

Suggestions	Reference
One commercial product, two feed supplements -3NOP (Bovaer®) and seaweed and asparagus can reduce CH_4 emissions by 40+% and 90%, respectively.	179
Modifying the diet of dairy cows, including increasing lipid concentration (up to 6%) and decreasing fiber concentration, without affecting the total energy intake, leads to a 15.7% reduction of intestinal CH_4 emissions from dairy cows.	184
CH_4 reduction strategies have two-way benefits for livestock production and the environment. A recent short-term in vitro trial tested the effectiveness of Mootral (a blend of garlic and citrus extract) on rumen fermentation characteristics, CH_4 production, and the bacterial community in ruminants. The results indicate that Mootral holds promise as a natural feed supplement for reducing CH_4 emissions while maintaining rumen health, making it a viable option for improving livestock production and mitigating environmental impact.	185
Enteric fermentation in farmed ruminants is a significant source of CH_4 and is the second-largest human contributor to global warming. Reducing CH_4 emissions from ruminants is crucial for ensuring sustainable animal production in the future. CH_4 production in the rumen is closely linked to microbial hydrogen production during fermentation processes.	186
Plant phytochemicals can significantly influence rumen methanogens, either directly by affecting the methanogens themselves or indirectly by modulating rumen protozoa. The use of plant extracts such as saponins, tannins, and essential oils to modulate the rumen microbiota- including both methanogens and protozoa- has potential benefits for animal nutrition. This approach not only reduces dietary energy loss but also helps mitigate environmental impacts by decreasing CH_4 production.	187
Paulownia, either as a new dietary component or in the form of its extract as a feed additive, has the potential to reduce rumen methanogenesis. This not only contributes to environmental protection but also decreases rumen biohydrogenation, ultimately improving the quality of milk and meat.	188
H_2 is the primary substrate for CH_4 production in rumen methanogenesis. Sulfate-reducing bacteria can compete with methanogens for H_2 in the rumen, thereby inhibiting CH_4 production. Enhancing the rumen sulfate reduction pathway is a promising strategy for reducing CH_4 emissions in ruminants. Future research should focus on determining the optimal levels of dietary supplementation with various sulfur (S) sources to reduce rumen CH_4 production while maintaining ruminant performance and health.	189
A mixture of eucalyptus (*Eucalyptus citriodora*) and poplar (*Populus deltoides*) leaf flour (50 g/h/day) contains 3.19 g of total phenolics, 2.30 g of phenolic tannins, and 0.71 g of condensed tannins. This mixture can be used as a plant feed additive to enhance the antioxidant status and immunity of buffalo calves, while also reducing intestinal CH_4 production, without negatively affecting performance and nutrient utilization.	190
Many agricultural practices can help reduce GHG emissions, with the most notable being improved management of cropland and grazing land, as well as the restoration of degraded land and cultivated organic soils.	191
A critical step is to accurately price environmental services-natural resources that are usually free or cheap-that lead to "overexploitation and pollution."	192

environmentally harmful activities. A primary focus should be to ensure that prices reflect all economic and environmental costs, including external factors. To achieve this, there must be secure and, where possible, tradable rights to water, land, common land use, and waste disposal sites. Harmful subsidies should be eliminated, and economic and environmental externalities should be incorporated into prices through selective taxation or resource use and waste charges. In some cases, direct incentives may be necessary. The payment system for environmental services is a crucial framework, particularly in relation to biomass resource systems. Herders, producers, and landowners can be incentivized to optimize the use of waste landfills, regulate water flows, protect soil, preserve natural landscapes, safeguard wildlife habitats, and facilitate carbon sequestration. In non-dense pasture-based production systems, the provision of environmental services is a major objective. One overarching lesson is that the livestock sector has such widespread environmental effects that it should be placed as one of the main axes of environmental policy. Efforts in this sector can yield substantial and diverse returns. As societies develop, the consideration of both environmental and human health issues will likely dominate policy discussions for the sector. Finally, it is crucial to establish appropriate institutional and policy frameworks at local, national, and international levels to implement these changes. This requires strong political commitment, increased knowledge, and greater awareness of the environmental risks associated with continuing the current trajectory, as well as the environmental benefits of transforming the livestock sector. Turning agricultural and livestock waste into biogas is one of the most effective strategies to mitigate deforestation. Thus, biogas technology is essential for preserving forests in Iran and globally. Many pathogens, such as viruses, bacteria, and parasites, are present in human sewage, animal excreta, and waste. When vegetable and animal fertilizers are used in their raw or undigested forms, these pathogens spread. However, AD and biogas production processes can significantly reduce these pathogens. Farmers can use the output from biogas plants as healthy fertilizer, and weed seeds are largely destroyed through AD. In this context, biogas production not only controls environmental pollution but also provides sanitary fertilizer that is free from weeds, parasite eggs, and other harmful elements. The daily production of vast amounts of waste in rural areas, with a high percentage of perishable materials, underscores the importance of biogas technology. Therefore, adopting AD and biogas production can be a critical step in reducing pollution, controlling weed growth, and enhancing agricultural sustainability.

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Competing Interests

The authors declare that there is no conflict of interest concerning the publication of the study.

Ethical Approval

This work was approved by the Ethics Committee of Kurdistan University of Medical Sciences, Sanandaj, Iran (IR.MUK.REC.1403.229).

Funding

None.

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