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REVIEW ARTICLE

A review of appropriate use of agroforestry residues for biogas production and prospects

R Chithra[1], K R Ramesh[1*], K T Parthiban[1], I Sekar[1] & P Subramanian[2]

[1]Department of Agroforestry, Forest College and Research Institute, Tamil Nadu Agricultural University, Mettupalayam 641 301, Tamil Nadu, India
[2]Department of Renewable Energy Engineering, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - rameshforest99@gmail.com

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Abstract

Making bioenergy from waste or residue is one of the innovative and valuable ways to use renewable resources in addition to wind and solar energy. Many poor countries can benefit from this as they attempt to address the enormous amounts of rubbish left in landfills. This waste could be liquid (oil and wastewater) or solid (food and agricultural and agroforestry wastes). These consist of waste or agroforestry residues, like tree stumps and leftover leaves from timber harvest. Its' all produced via an agroforestry system. Waste has a detrimental impact on the ecosystem and, consequently, all living organisms. One solution to this waste issue is to use garbage as a resource to produce beneficial products like biogas using compressed bioenergy production equipment. In this work, bibliometric methodologies were employed to assess global research advancements in bioenergy production from garbage through the Scopus database and developments in bioenergy production from waste. This review study assumed that agroforestry waste may be an optimistic substrate for biogas production in developing countries due to its widespread availability. Compressed biogas production, among other alternatives, is a workable solution to the countrys' current energy issues and is safe for the environment because it emits no pollutants.

Keywords: agroforestry; biodigesters; biofuel; green energy; waste

Introduction

One practical approach to reducing carbon emissions and using renewable energy sources is to use compressed biogas-producing technology for agroforestry leftovers. This method uses anaerobic digestion of agroforestry residues, including woody biomass and crop residues, to produce biogas (1). This biogas is helpful for several uses, including power production, heating and vehicle fuel, provided it is compressed and subjected to additional processing.. Compressed biogas production technology for agroforestry residues presents a significant opportunity to address environmental concerns and fulfil the growing energy demand (2). This technique produces compressed biogas from agroforestry leftovers, lessens reliance on fossil fuels and slows global warming by producing a renewable energy source. Agro-industrial residues and forestry wastes can all be made by an agroforestry system (3, 4) (Fig. 1).

Utilizing bioenergy could reduce dependency on oil imports, which are volatile in the geopolitical sphere and susceptible to price fluctuations. By 2030, India hopes to have 500 GW of installed electrical capacity produced by non-fossil sources. The nation can achieve this objective with the help of bioenergy. The Indian government aims to reduce the countrys' carbon footprint by 30 to 35 % by 2030. The need for environmentally friendly methods to create substitute materials from agricultural and forestry waste, such as straw and bark that are typically wasted, is great for solving this issue (5). As biofuel is becoming a popular substitute for non-renewable resources, it can produce various products in a biorefinery in addition to energy (6-8). The advantages of agroforestry waste are making it more and more popular and they will eventually contribute significantly to bettering the economic and environmental circumstances of the nation.

Overall view of biogas

In the seventeenth century, anaerobic digestion was first recognized as producing flammable gas by decomposing organic waste in a covered environment. Baptita VanHelmont was the first to realize that the decomposition of organic substances may result in flammable gases in the seventeenth century (9,10). Scientific advancement in the 1930s led to studies (11, 12) and others to determine which anaerobic bacteria were present and what conditions encouraged methane production.

Many countries have adopted or are thinking about ways to lessen the environmental impact of trash disposal due to these ecological demands. Digesters are used in over 35 industries, including those that deal with chemicals, fibre

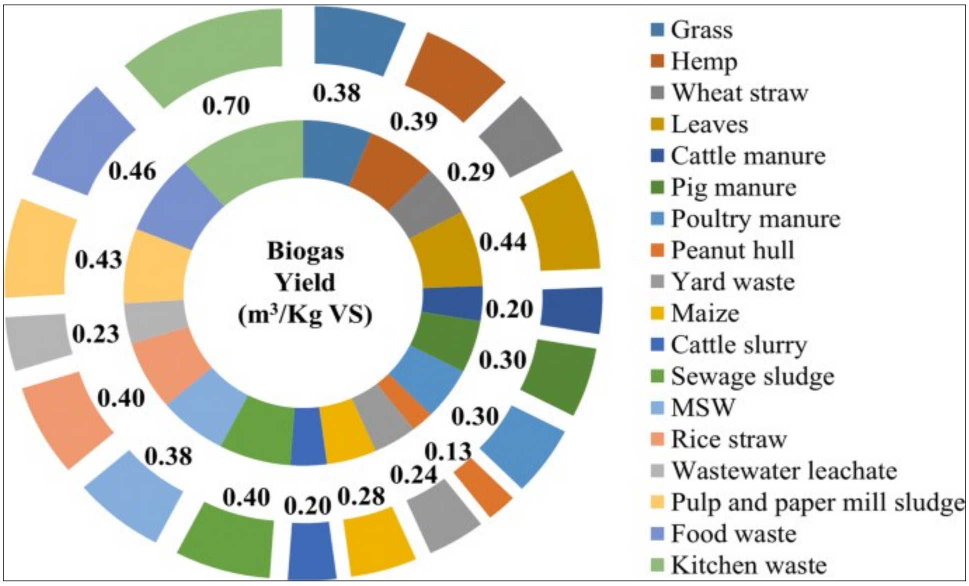

Fig. 1. Biogas is produced from a variety of sources (4).

and others (9). MSW processing facilities have evolved significantly towards commercial use in recent years and pretreatment increases treatment capacity from the perspective of the municipal facility. The time it takes for MSW to digest is one of the numerous technical problems with this process. Despite being commercially accessible and in use, composting technologys' potential for further application is primarily limited by process costs and environmental concerns. Although biogas makes up a tiny portion of the energy economy of most developed countries, it is generally increasing slowly in tandem with the expanding use of renewable energy (9).

Biogass' contribution on a worldwide scale

Renewable energy sources accounted for 14.4 % of the worlds' energy consumption in 2019. Biogas accounted for just 1.6 % of all renewable energy sources in 2019. Because biogas depends on feedstock availability and policies that promote its production and usage, its development has been unequal globally. About 30 % of it was used in buildings, primarily for heating and cooking in residential areas. The remaining 30 % was converted to biomethane, which was used as a transportation fuel or combined with petrol networks. Although biogas has many uses, over 70 % of it generates heat and electricity, with an equal distribution between facilities that exclusively generate and generate heat. Only 2 % of the worlds' waste and feedstocks appropriate for biogas generation are currently being used for that purpose, per the World Biogas Associations' July 2019 evaluation of the potential of biogas globally. (13). According to the research, biogas recovery from these easily accessible feedstocks may provide up to 6 - 9 % of the worlds' 36–54 EJ current basic energy demands, using technology that is already available and could be put into use right away (14, 9).

The organic waste, which was estimated to be between 17 and 128 EJ, provides an example of the uncertainty in these Fig. 2. In any case, the 1.43 EJ that the biogas sector produced in 2019 shows how much room there is for it to expand globally (15, 16).

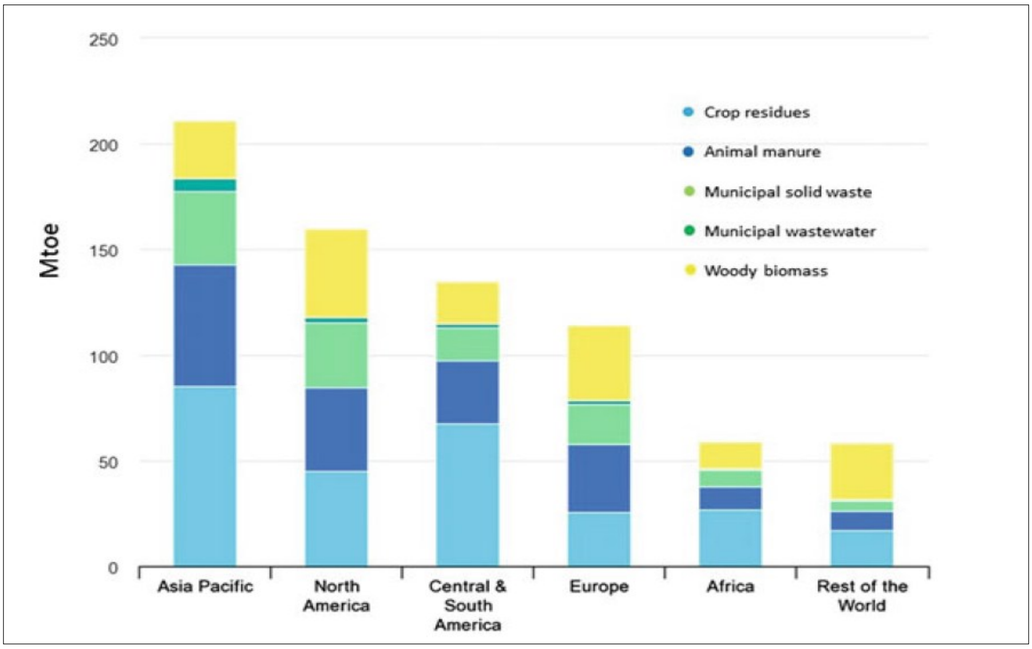

Fig. 2. Energy potential of biogas or biomethane by feedstock source (15).

According to the World Bioenergy Association, 2021, biogas production reached 1.43 EJ in 2019, a 5.1 % increase over 2018. Nearly 54 % of the output took place in the European Union. Between 2019 and 2000, biogas production increased about fivefold, from 0.28 EJ to 1.43 EJ. Although Europe saw the most significant rise in output, biogass' overall contribution to the global energy landscape is still relatively small (0.2 %). In Europe, 13.5 million tonnes of biogas were produced annually from 1.5 billion tonnes of agricultural biomass because of the low price of the easily accessible raw materials and the governmental backing that created a robust market for biogas (17). The European biogas plant market size was USD 1.67 billion in 2020. The market is expected to grow from USD 1.87 billion in 2021 to USD 3.47 billion in 2028 at a CAGR of 9.2 % in 2021-2028. In Europe, there are around 15,000 biogas plants. With the robust growth of agricultural biogas plants, the primary feedstock option that supported Germanys' biogas sector was energy crops; but, in recent years, the policy has moved more in favour of using crop residues, sequence crops, livestock waste and methane capture from landfills. A significant European initiative to promote industrial biomass-based fuel production by modifying tax concessions and funding biogas research and development initiatives. Green petrol fuels are to meet environmental sustainability standards specified by the European Union. Nearly 90 % of biogas produced in the United States currently comes from landfill gas collection, which has been the biogas pathway (9).

Southeast Asian Biogas Production

After reviewing worldwide biogas production, this part will look at Southeast Asia. Though it can produce the most, the Clean Development Mechanism provided funding for the development of biogas, especially from 2007 to 2011. The warm environment and abundant rainfall encourage the lush vegetation perfect for producing biogas. The following section discusses the significant substrates in Southeast Asia. Livestock dung, palm oil and cassava are the three most often used substrates of renewable energy. Manure from pigs and chickens makes up most of the livestock waste (Table 1). Although they are much less numerous, there are some molasses and ethanol biogas facilities (9).

Status of biogas contribution in the national level

Long-term imports now meet approximately 50 % of Indias' natural gas and approximately 77 % of its crude oil needs. By 2022, the Indian government wants to cut this import by at least 10 %. Only 0.06 % of the potential 32 million tonnes of CBG that may be produced in the country are now made (9).

Table 1. Classification of Southeast Asian substrates for biogas generation

Name of the substrates	Remarks	References
Cassava	◊Over 90 % of cassava-starch plants in Thailand also use wastewater to create biogas. The amount of suspended organic particles in the wastewater is considerable. ◊ An anaerobic fixed film reactor was created to clean wastewater and generate biogas from cassava starch plants.	(9)
Palm oil mill effluent	◊Southeast Asian nations are the worlds' biggest palm oil producers. ◊The effluent from fresh palm oil mills is hot (between 60 and 80 °C), acidic (with a pH of 3.3 to 4.6) and thick, brownish, with a high-fat, oil and grease content. ◊Various modifications from standard anaerobic plants have been developed for POME wastewater, including attached growth anaerobic reactors, anaerobic fluidized bed reactors, anaerobic filters, anaerobic sludge blanket processes, anaerobic baffled bioreactors and integrated anaerobic treatment processes.	(18)
Livestock waste	◊Another popular source for biogas production is livestock waste. ◊In Thailands' past, biogas systems have relied on agricultural waste, specifically wastewater and manure from pig farms. ◊A conversion factor in Thailand converts a livestock unit into a biogas production rate.	(19, 20)
Municipal solid waste	◊Municipal solid waste is generated within a municipality by households, industries and commerce. ◊Its composition and quantity are variable, with organic matter constituting about 25-75 % of the total MSW. ◊The potential to separate the organic biodegradable portion from the overall MSW has increased interest in the anaerobic digestion of MSW. ◊Additionally, the generation of renewable energy, reduction of landfilling and mitigation of pollution are other advantages.	
Industrial waste	◊Industrial wastes are byproducts, residues and wastes that result from various industrial activities. ◊They include waste from the pulp and paper industry, food industry, petrochemical refinery waste, textile industry and liquid biofuel production waste. ◊The resistant chemical characteristics and low biodegradability of approximately 30 to 50 % have prevented the widespread use of other industrial wastes as a substrate in anaerobic digestion, aside from waste from the food industry.	(9)
Other waste sources	◊Less common sources of substrates for biogas production include wheat straw, corn stover and sugarcane. ◊Although its lignocellulose concentration slows the decomposition process, wheat straw is a typical example of agricultural waste that can be used as a substrate for biogas production. ◊The leftover corn stover from the maize harvest has the potential to be used as a substrate for the production of biogas. Because of its energy potential, sugarcane bagasse is another agricultural waste that can be used as a substrate for co-digestion. It is a byproduct of the industry that mills sugar.	

Current patterns of using agroforestry waste for a range of applications

Branches, leaves, pruning and other organic waste generated by these agroforestry systems can be recycled and used to maximize the systems' overall efficacy and sustainability (21). One of the primary uses of agroforestry waste is as a sustainable energy source. Our current economy is linear, unsustainable and unstable. The three pillars of the linear economy are waste, consumption and output. As a result, this economic model can only be implemented with infinite resources. Resources are expected to increase when the worlds' population approaches 10 billion in 2050 (22, 23). Policymakers also support sustainable development, which is encouraged by the existing economys' transition from fossil fuel-based energy and products (24). However, it also has drawbacks, such as worsening effects on land usage and overuse of biomass (25). Inappropriate development methods and poor resource selection, including forest and agricultural resources, are also factors.

Agroforestry relieves forest stress since farm-grown trees provide fuelwood and help meet local energy needs. People have been using wood as an energy source to meet their basic needs for thousands of years. There is no end to this. In particular, the production of charcoal for urban energy is a major contributor to the systematic loss of dryland forests worldwide (26). In addition to more effective production and use of firewood and charcoal, other sustainable bioenergy sources must be promoted to counteract the current deforestation.

Sustainability of biogas generation using agroforestry waste resources

The manufacture of biogas from forest leftovers was suggested by (27) (Table 2 & 3). Pine needles and bark yielded the highest amount of volatile solids. The biomass found in northern Portugals' forests and farms was defined to meet government targets. Measurements were made of the increased calorific value and chemical makeup of the residues from agriculture, forests and shrubs. Compared to the values found in the agricultural forestry residues, the shrub samples' calorific values were higher and statistically different (27).

The numerous components found in agro-industrial wastes contribute to the overall synthesis of biofuel from these wastes. Adding grains and vegetable waste raises the proportion of carbs, whilst meat and fats increase the content of protein and lipids. Utilizing agro-industrial wastes to produce biofuels is an interesting area of study. Wastes from animal husbandry, farms, livestock and other agricultural processing industries are efficient sources of biofuels. Their primary constituents include proteins, lipids, fibres, other organic components and carbohydrate polymers, including cellulose, hemicellulose and starch. The ecology may suffer if these wastes are not disposed of appropriately due to their high organic content (28).

Table 2: Various softwood material sources

S. No.	Substrate	Pretreatment	Type of digestion	References
1.	Spruce	Alkaline	Thermophilic	(29)
2.	Pine needle leaves	Untreated	Mesophilic	(30)
3.	Pine branches and cone	Alkaline	Mesophilic	
4.	A mixture of spruce and pine	Iconic liquids	Mesophilic	(31)

Table 3. Different sources of hardwood forest trees

S.NO	Substrate	Pretreatment	Type of digestion	References
1.	Birch	Alkali	Thermophilic	(29)
2.	Willow	Steam explosion	Mesophilic	(32)
3.	Willow and Cow manure	Steam explosion	Mesophilic	(33)
4.	Eucalyptus	Hot water extraction	Mesophilic	(34)
5.	Poplar	Alkaline	Mesophilic	(35)
6.	Maple	Untreated	Mesophilic	(36)
7.	Black locust	Untreated	Mesophilic	(37)

Global and Indian biogas energy production status from agroforestry waste

This work employed bibliometric methodologies to assess global research advancements in bioenergy production from garbage using the Scopus database developments in producing bioenergy from waste. There are currently roughly 6254 publications on the generation of bioenergy from garbage. These outcomes are consistent with recent findings suggesting a shift in the production and storage of renewable energy in Asia, Europe and other South American nations. Furthermore, these data have shown how larger nations are integrating bioenergy even more, with the building sector and industry seeing a 2.1 % increase between 2018 and 2019 (22).

Anaerobic organic matter breakdown contributes to the creation of biogas.

Organic matter frequently undergoes anaerobic decomposition in natural environments, including marshlands, swamps, animal stomachs and lake or pond sediments (9). Since it tackles critical global challenges, including waste management, energy security and environmental concerns, several distorting processes can break down organic materials, such as biomass, crop residue, sewage sludge, animal manure, industrial wastewater and municipal solid waste. The environment is carefully regulated in an AD to optimize the generation of biogas (38).

Process of anaerobic organic matter digestion

In anaerobic digestion, diverse microbial populations break down biodegradable materials and create biogas. Hydrolysis, acidogenesis, acetogenesis and methanogenesis are these four main processes. In short, the process hydrolyses big organic molecules into smaller ones, which are then transformed into acids, resulting in biogas (9).

Production of biogas through hydrolysis

The initial stage of producing biogas is hydrolysis. It breaks down complex biological components. Hydrolytic microorganisms break down organic molecules by producing extracellular enzymes produced by anaerobic bacteria (Table 4). These hydrolytic bacteria can be either obligatory or facultative anaerobic microbes. As a result, they aggressively break down organic molecules, whether or not oxygen is present (9).

Table 4. Microorganisms used for hydrolysis of complex organic molecules

Complex organic compounds	Resulting simple biochemical molecules	Extracellular enzymes	Hydrolytic Microorganisms	References
Carbohydrates	Soluble sugars	Amylase, cellulase, cellobiase, hemicellulase, xylase,	*Acetovibrio cellulíticus*, *Bacillus*, *Bacteriodes*, *Clostridium*, *Lactobacillus* and *Staphylococcus*	
Proteins	Peptides and amino Acids	Protease and peptidase	*Bacteriodes*, *Butyrivibrio*, *Clostridium*, *Fusobacterium*, *Peptococcus*, *Proteus vulgoris*, *Selenomonas* and *Streptococcus*	(38,39)
Lipids	Long-chain fatty acids	Lipase	*Clostridium*, *Eubacterium limosum*, *Mycobacterium* and *Streptococcus*	

A pretreatment procedure is frequently required for feedstocks with complicated structures, such as lignocellulose, to increase the rate of hydrolysis and general digestibility. The size, complexity and kind of biodegradable material all affect the hydrolysis reaction rate. The process that limits the rate at which biogas is produced is hydrolysis, which can take days for feedstocks with significant lipid or solids contents. As a biological process, pre-treatment breaks down organic material before it enters the digester. Temperature, pH, organic matter concentration, surface area for enzyme breakdown and inhibitory chemicals are the main environmental elements that affect it. After hydrolysis, the total organic content remains constant because pre-treatment reduces complicated material to smaller molecules. (38, 39).

Acidogenesis of biogas synthesis

Acidogenesis follows the hydrolysis process. It produces intermediaries for additional digestion. During fermentation, simple biological molecules are transformed into hydrogen (H_2). Bacteria carry out this phase, often called acidogenic bacteria or acidogens (Fig. 3). The fastest method in creating biogas is acidogenesis, which happens quickly. VFA buildup may lower the systems' pH and possibly cause process failure (38, 39).

Acetogenesis of biogas synthesis

The process of converting the intermediates (alcohol and VFAs) generated during acidogenesis into acetate (acetic acid) is known as acetogenesis. This stage is crucial since 60-70 % of the methane produced is due to acetate (40). Two main processes create it: Syntrophic acetogenesis, in which VFAs undergo oxidation to produce smaller molecules (acetate and H_2). Homoacetogenesis, in which H_2 and CO_2 combine to form acetate

Low H_2 concentrations (less than 100 ppm) are necessary for acetogenic bacteria to grow and function. The two types of bacteria have a syntrophic interaction. Thus, syntrophic acetogenesis bacteria or syntrophic acetogens are the popular names for H_2-generating acetogenic bacteria. Even though acetogenesis has a quick reaction time, this anaerobic bacterium has a lengthy lag phase necessary for environmental adaption. The syntrophic acetogens that are frequently identified in anaerobic digesters include *Syntrophomonas wolfei* and *Syntrophobacteri wolinii* (41).

Furthermore, *Desulfovibrio* species may metabolize lactate or ethanol to produce acetate without sulphate (42). Among other microorganisms referred to are homoacetogenic bacteria or homoacetogens (43). Autotrophic homoacetogens use H_2 to make acetate and CO2 as a carbon source, per (9).

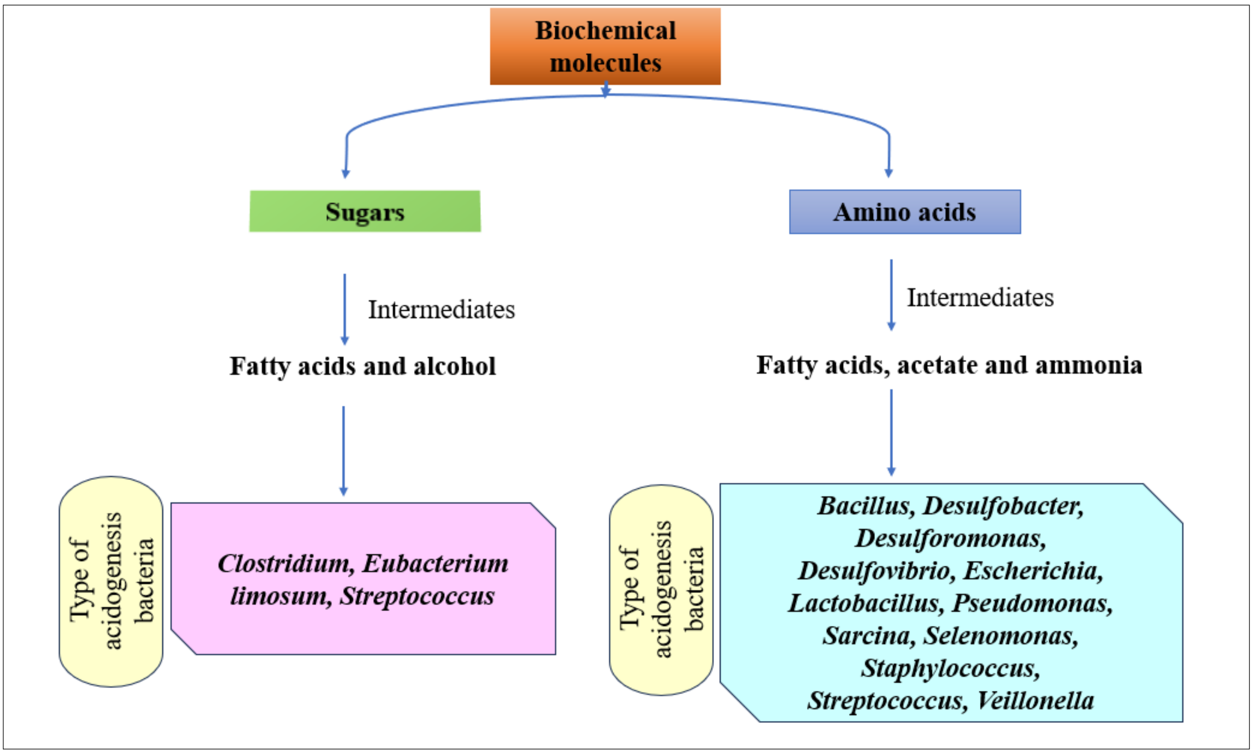

Fig. 3. Microorganisms involved in acidogenesis.

Methanogenesis of biogas synthesis

Methanogenesis is the process by which methanogens use an anaerobic source to produce methane in a strictly anaerobic environment (9). The main bacteria that produce biogas are shown in Fig. 4. The collection of methanogens that produce methane can be divided into two main pathways

Acetotrophic methanogens

Acetate is essential for effective AD through various metabolic mechanisms since the two major genera, Methanosarcina and Methanosaeta, produce methane (44, 45).

Hydrogenotrophic methanogens

Hydrogenotrophic methanogens carry out the final 30 % of methane synthesis in AD. These methanogens use the H_2 generated during acetogenesis to convert CO_2 to methane. Since acetogenesis requires low H_2 concentrations, hydrogenotrophs are essential to steady and effective AD. Formate, carbon monoxide and alcohol can all be used by certain hydrogenotrophic methanogens to decrease CO_2 and produce methane (40).

Utilization of biogas and composition of raw materials

By converting biogas to biomethane, the heating value can be raised to about 35MJ/Nm3. This entails purging the raw biogas of most contaminants and carbon dioxide. Transportation, chemical manufacture, heat generation and electricity generation are among the uses for biogas (Fig. 5). Around the world, most biogas (27 %) is used for heating. In comparison, the majority (64 %) is used to produce renewable power. The remaining 9 % of biogas can be injected into the natural gas grid or used as biomethane in the transportation industry (9) (Table 5).

Systemic storage facilities of biogas

The digester head area typically stores biogas generated by anaerobic digestion systems. This one is the volume right above the digester. It is possible to set this storage volume to correspond with the daily production rate of biogas. It is also necessary to balance biogas storage with its use and consumption. Additional storage space can be used as buffering to guarantee uninterrupted biogas supply to its final usage. Changes in feedstock or operational challenges may cause shortages (Table 8). Additional storage facilities are often costly, but they are required in plants that require significant buffering due to safety and redundancy requirements (9). Table 6 illustrates how biogas storage systems are categorized based on the storage tanks' volume and pressure.

Applications and Advantages of biogas

There isn't a single, precise number for the composition of natural gas because it varies depending on geography. For any power generation technology to be effective, it must be able to handle different biogas compositions. Biogas is compatible with several technologies. These small-scale power production technologies can handle biogas but are typically powered by natural gas (Fig. 6-7) (9, 46).

The main benefit of biogas systems is that they recycle all of this material and create soil products and sustainable energy that replace fossil fuels. In addition to lowering greenhouse gas emissions, biogas systems preserve the natural ecosystem (Table 7). Use natural fertilizers that don't originate from fossil fuels to promote soil health and provide reliable, baseload renewable electricity. (47).

Table 5. Estimate the methane content and biogas yield based on the kind of raw material.

Raw material	Methane volume (%)	Biogas yield (m³ / ton fresh feedstock)	References
Liquid cattle manure	55-65	20-30	(9)
Liquid pig manure	60-70	25-35	
Cattle manure	55-65	40-50	
Pig manure	55-65	55 -65	
Poultry manure	55-65	75-85	
Organic waste	55-65	90-110	
Napier grass	50-60	70-100	
Corn silage	45-55	150-200	

Table 6. Storage of biogas organized by pressure

Pressure level	Pressure	Application	References
Low	0.005-0.5 kPa	Single membrane	(9)
Medium	0.5-5 kPa	Double membrane / fixed dome	
High	0.5-30 MPa	High-pressure tanks	

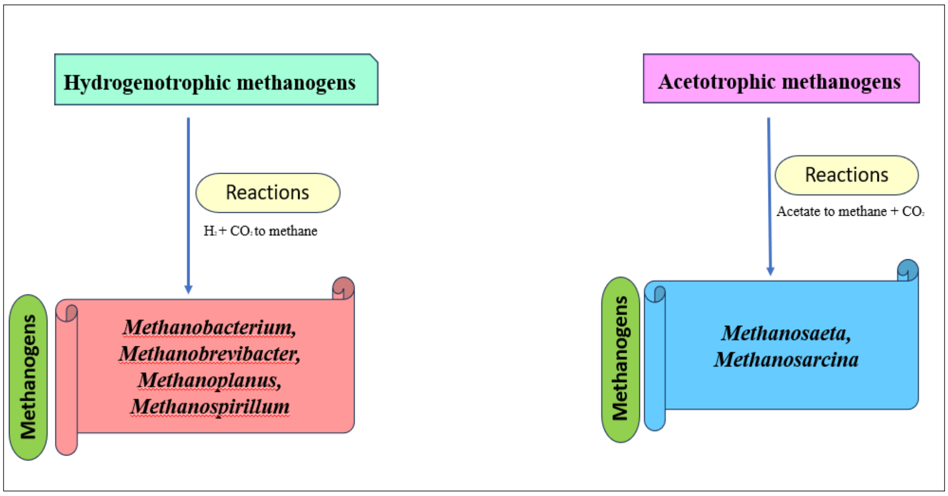

Fig. 4. Microorganisms involved in methanogenesis (38, 43).

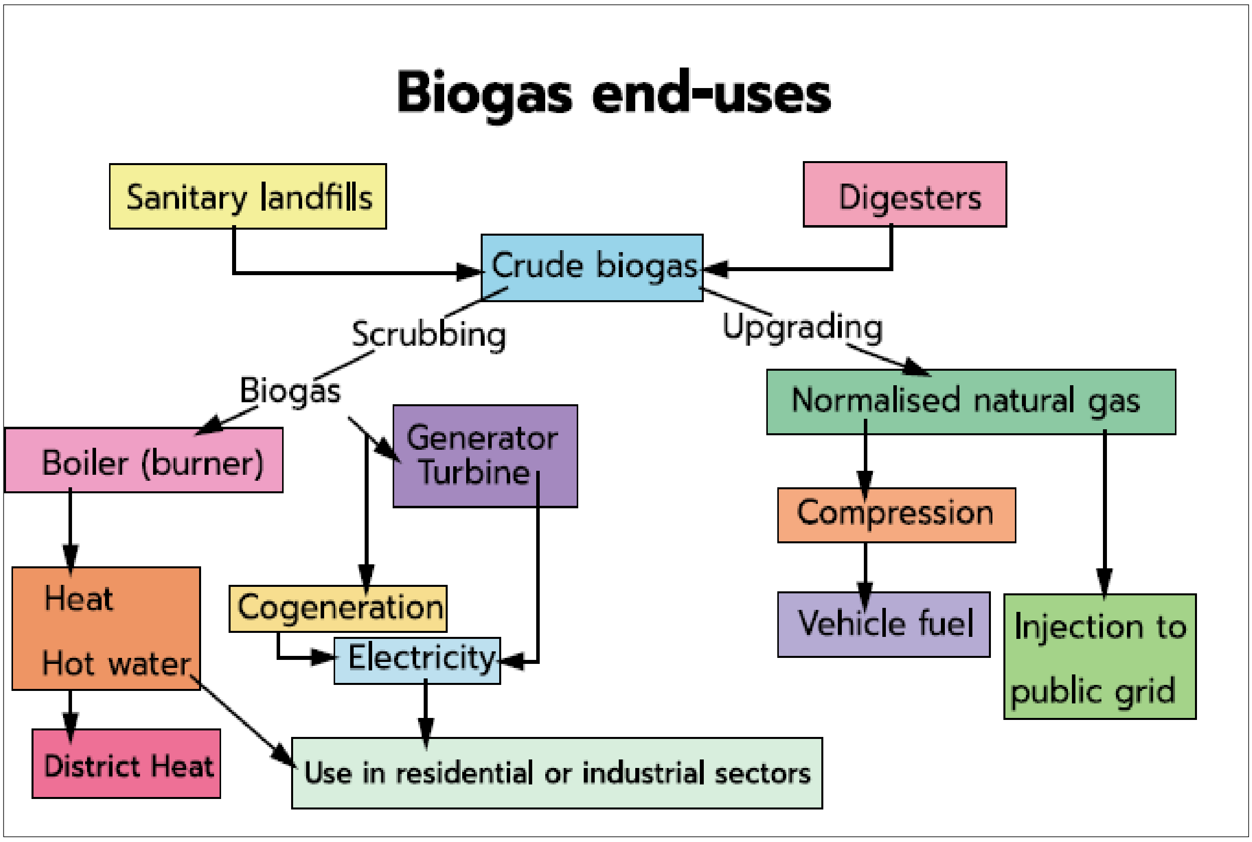

Fig. 5. Applications for biogas end use (9).

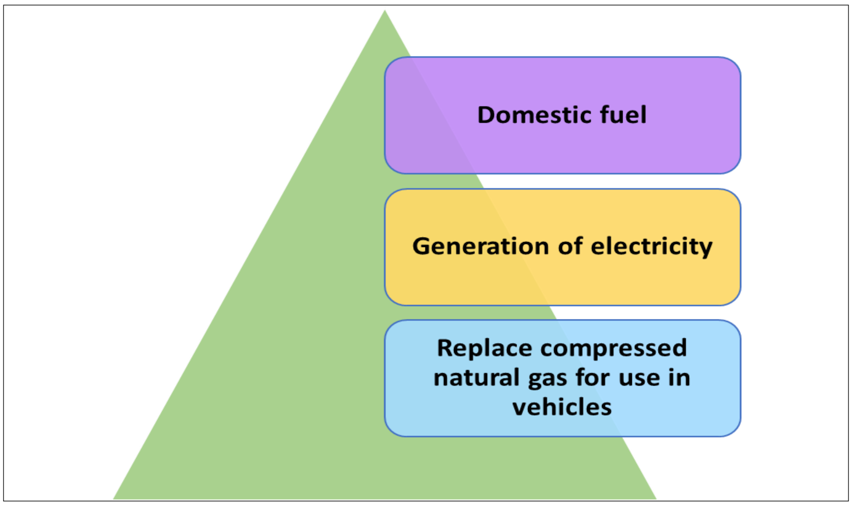

Fig. 6. Applications of biogas benefits of biogas.

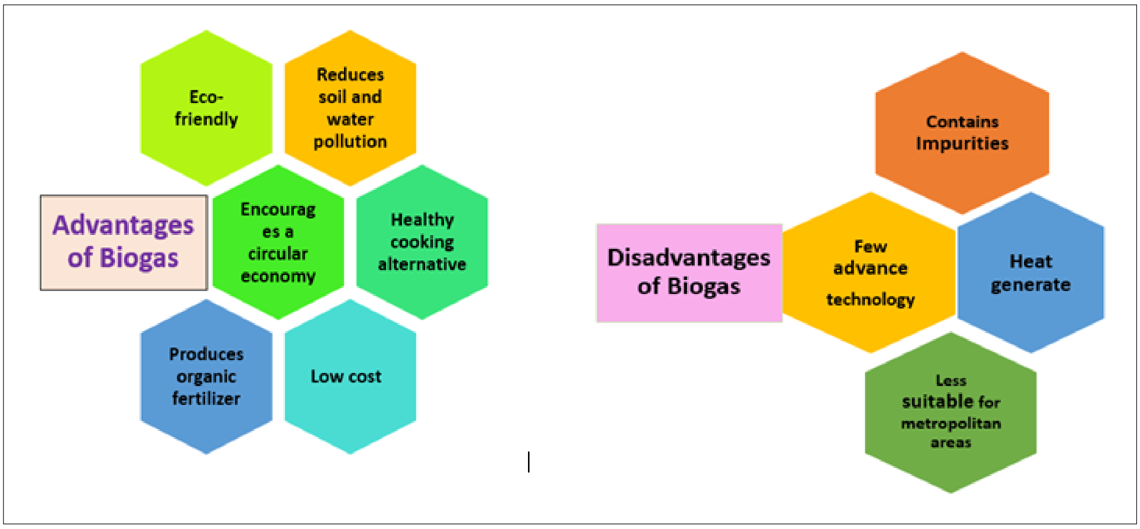

Fig. 7. Advantages and disadvantages of biogas.

Table 7. Benefits of biogas categorization

Environmental benefits	Economic benefits	Energy benefits	References
Recycle manure while producing renewable energy and soil products.	A cost-effective solution to turning a high-cost deliverable like waste treatment into a revenue-generating opportunity for farmers and rural communities	A renewable source of energy that is a direct replacement for non-renewable, carbon-intensive fossil fuels	
Reduce carbon emissions	Create new revenue streams in rural areas, building resiliency against commodity price fluctuations.	Biogas supports distributed energy generation, which means lower transmission and transportation costs, reduced impact and higher reliability of electrical grids.	
Digestate can replace costly synthetic fertilizers. It can increase plant growth by 10-30 % compared to synthetic fertilizers.	Can reduce farm costs for animal bedding fertilizer and generate new revenue streams	Systems with gas storage can provide renewable electricity on demand in minutes, reducing the need to turn on fossil -fueled power plants to meet peak demand.	(47)
Plants absorb soil nutrients, like nitrogen or phosphorus, more quickly than raw manure.	A driver for economic growth and offers local jobs in construction, engineering, project management and More reduces the volume of waste, meaning that costs are often lowered for facilities like wastewater plants	Renewable Natural Gas procured from biogas can be used interchangeably with natural gas for heating, electricity and producing quality biomethane and transportation fuel. Biogas is currently the most sustainable way to minimize these emissions.	

Table 8. Resolving typical issues with a biogas system

Problems	Effects	Impact	Correcting measures	References
Hydraulic overloading	Microbes in the system are washed out causing lower solid retention time than the design value • The flow pattern and condition become unsuitable for microbial growth • The wastewater retention time becomes lower than the design value	% CH_4 decreases • % COD removal decreases • Solids in the effluent increases • VFA/ALK increases	Reduces/stops the influent feeding • Controls the flow rate of wastewater so that it does not exceed the designed value • Adds more inoculum or sludge from other biogas systems	
Organic overloading	There is an imbalance between organic matter and microorganisms in the system • Causes unsuitable conditions for microorganisms to grow	% CH4 decreases • % COD removal decreases • VFA/ALK increases • pH decreases	Limits the OLR below 2 kg COD/m3day by decreasing the influent flow rate • If VFA/ALK is high, adds alkalinity, e.g., caustic soda or lime, to maintain the pH value of the system • Recirculates the effluent from the post-treatment system to dilute the concentration in the reactor and to maintain the alkalinity within the system • Adds more inoculum or sludge from other biogas systems	(9)
Toxic substances	Harms the living microbes and reduces the concentrations • Causes unsuitable conditions for microbe growth	Biogas yield decreases • COD removal plunges rapidly • VFA/ALK increases	Reduces/stops the influent feeding • Investigates the possible species of toxic substances in the wastewater • Consults an expert or designer for the solution	
Organic under-loading	The growth rate of microorganisms is low	Producing too small quantity of biogas from the system	Increases the flow rate of influent • Recirculates the effluent back to the digester to maintain the concentration of organic matters in the system	
VFA/ALK > 0.4 or low pH < 6.8	Causes unsuitable conditions for methane-producing microorganisms to grow	COD removal plunges rapidly • Rapidly declining pH • Biogas production decreases	Re-balances the VFA/ALK by adding caustic soda or lime • Recirculates the effluent from the post-treatment system to maintain the alkalinity within the system • Investigate possible causes of low biogas production	
Low biogas production	Inadequate quantity of biogas	Low utilization of biogas • Low financial return	Investigates possible causes of low biogas production • Analyze important parameters, e.g., feed flow rate, COD, pH and VFA/ALK	
Too high concentration of biomass (VSS too large)	The balance between microorganisms and food is poor Sludge production is too high	Excessive sludge needs to be withdrawn frequently • Increased costs of sludge management	Increases the sludge removal • Analyze important parameters, e.g., feed flow rate, COD, pH and VFA/ALK to determine causes of the problem	(9)
Too low concentration of biomass (VSS too small)	The balance between microorganisms and food is poor Sludge production is too low	COD removal efficiency is lower • The effluent SS might be high, indicating microbe washing out	Decreases or stops the sludge removal • Add some sludge from other biogas facilities to increase biomass in the system • Checks the COD:N:P ratio of the influent • Check if there is any toxic substance in wastewater	

Conclusion

Harnessing agroforestry residues for biogas production is a vital strategy for promoting energy sustainability while addressing environmental challenges. The significance of turning organic waste from agroforestry systems into compressed biogas, renewable energy, is emphasized in this review. Through anaerobic digestion, agricultural and forestry residues such as tree stumps, leaves and crop waste can be effectively transformed into biogas, which can then be utilized for electricity generation, heating and transportation. The global and regional potential for biogas production is substantial. Although Europe continues to lead the world in biogas production, Asia, especially China and India, has enormous untapped potential. The United Nations Sustainable Development Goals and other global sustainability programs align with Indias' aim to increase the proportion of biogas in its energy mix. By capitalizing on agroforestry waste and other organic materials, nations can significantly lower their carbon footprints, enhance energy security and support rural economic growth by generating employment opportunities in the biogas sector. The biogas production process has been extensively researched, showcasing the effectiveness of microbial digestion in methane generation. However, several challenges persist, including technological constraints, financial viability and the necessity for favourable government policies. Implementing pretreatment methods like alkaline treatment and steam explosion can improve biomass digestibility, leading to higher biogas yields.

Furthermore, advancements in biogas storage and upgrading technologies can enhance its applications across various industries. By integrating biogas technology, agroforestry systems contribute to a circular economy, transforming waste into valuable energy and soil nutrients. This approach reduces deforestation, alleviates forest pressure and offers a sustainable alternative to traditional biomass fuels such as wood and charcoal. Effective policy interventions play a crucial role in driving this transition. Governments must invest in research, provide financial incentives and establish regulatory frameworks to accelerate the adoption of biogas technology. Despite its numerous advantages, biogas systems encounter operational hurdles such as hydraulic overloading, organic underloading and the presence of toxic substances. Biogas plants will operate more efficiently and last longer if system performance is optimized, microbiological balance is maintained and storage capacity is increased.

Additionally, the widespread adoption of biogas as a mainstream energy source requires increased public awareness and collaboration among key stakeholders, including governments, private enterprises and research institutions. An ecologically benign, economically viable and sustainable substitute for traditional energy sources is biogas production from agroforestry leftovers. Global climate change mitigation, efficient waste management and energy security can all benefit from its widespread use. Biogas has the potential to revolutionize the renewable energy industry and open the door to a cleaner, more sustainable future by giving priority to technological advancements and regulations that support them.

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Authors' contributions

KR helped in choosing the review topic and its overall outline. KP, IS and PS participated in giving ideas related to the topic and drafted the manuscript. All authors read and approved the final manuscript.

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