Chapter 4
Anaerobic Digestion for Bioenergy Production Using Solid Animal Waste: New Avenues

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Abstract Waste production around the globe has become an essential topic of concern since this accumulated waste has resulted in environmental hazards. Anaerobic digestion produces biogas and increases methane production using an optimum substrate. The biogas production from anaerobic digestion of different wastes is highly dependent on process of biodegradation and operating at optimum conditions increases the process efficiency. In biogas production, feedstock composition is the key factor—more methane yields depending on the feedstock type. The digestion rate of organic wastes depends on the relative number of key components. Also, the quantity of the mixture includes physical factors like temperature and pressure. Little information is available for optimum conditions of anaerobic digestion. Therefore, it is suggested that optimum conditions for anaerobic digestion and co-digestion should be explored. Anaerobic digestion provides an alternative green and efficient solution for toxic waste management and energy production. So, this review emphasizes the anaerobic process, enhancement of biogas production, fermentation efficiency, and economic and environmental advantages. Further, the factors influencing anaerobic digestion and the effect of key and trace elements will be discussed.

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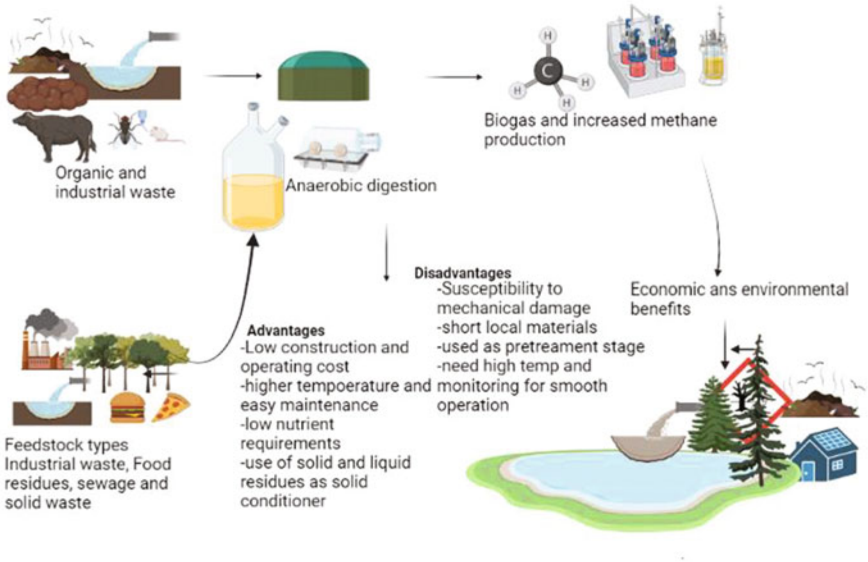
Graphical Abstract



Keywords Biogas · Anaerobic digesters · Biofuel · Free energy · Feedstock

4.1 Introduction

As a feedstock for biogas production, anaerobic digesters utilize various organic resources. However, there are scientific, technical, and legal restrictions adhere to some restrictions whether feedstock is animal manures, food waste, or wastewater effluents (Algapani et al. 2018; Tabatabaei et al. 2010). Furthermore, the feedstock should be a liquid mixture with high moisture content. Common digesters, such as mesophilic complete mix tank digesters, work best with a solids-in-water ratio of 4–8%. Depending on the system's functional architecture, different moisture contents are necessary. Anaerobic digestion (AD) has grown in popularity as more renewable energy sources have been available worldwide. AD results in the generation of biogas in two phases. Hydrolysis phase is first phase in which organic matter is transformed of into CO_2, fatty acids, and hydrogen. Second phase is methanogenic phase which involves decomposition of fatty acids into methane. Biogas is made up of methane, CO_2, and other trace components. The essential technique is the same for both large plants and tiny reactors. Pre-treatments and substrate co-digestion are becoming more common to improve biogas output. The installation location also influences reactor design and substrate choices. Biogas upgrading aids in boosting the gas's utility for various applications. The economic advantage is determined by multiple parameters, including location worldwide and the quality and amount of accessible substrate. To remain lucrative, AD processes rely substantially on government subsidies. AD profitability is especially important in developing countries because this technology improves human life in these locations. The chapter takes a detailed look at AD technology, discusses AD economics, and suggests future studies to improve the technology (Arshad et al. 2018).

4.1.1 Anaerobic Digestion

Anaerobic digestion is a sequential process in which microorganisms degrade biodegradable material in an anaerobic environment. It is used in both industries and domestic purposes for the production of fuels or to manage waste materials. Primarily fermentation is used in industries to produce food products. For yoghurt production in home fermentation, anaerobic digestion is used. Anaerobic digestion naturally occurring in soil lakes and ocean basins is usually termed anaerobic activity. In 1776, Alessandro Volta discovered that anaerobic digestion is the primary source of methane that begins with the hydrolysis of the input material by bacteria. During this process, carbohydrates and other insoluble polymers are degraded to their soluble derivatives and made assessable to other bacteria. Acidogenic bacteria convert sugars an amino acids into hydrogen, organic acids, carbon dioxide, and ammonia. The bacteria also convert the organic acids into acetic acid with hydrogen, carbon dioxide and hydrogen as additional products in a process called acetogenesis. At last, these products are converted into methane and carbon dioxide by methanogenic bacteria. Methanogenic archaea play an essential part in the anaerobic treatments of wastewater. Biodegradable sewage and waste sludge are treated by anaerobic digestion. The integrated system of waste management reduces the atmospheric emanation of methane gas. The biogas produced comprises carbon dioxide, methane, and trace amount of other contaminant gases. It is directly used as a fuel in power and heat gas engines. Additionally, the digestate is enriched with nutrients and can be used as a fertilizer (Aslam et al. 2018; Azzahrani et al. 2018).

4.1.2 Utilization of Animal Wastes for Bioenergy Production

If effectively recycled, many beneficial elements are found in animal waste and could be used as a good fertilizer for crop and energy production. Animal dung is a significant source of potassium, phosphorous, and nitrogen. Biogas is a renewable energy source produced by the anaerobic degradation of organic waste. Modern anaerobic digesters use air-tight chamber, where bacteria convert the solid manure into biogas that can be used for electricity production. Recently, the most frequently used biofuels are biogas and bioethanol. Biogas is generally produced by degrading

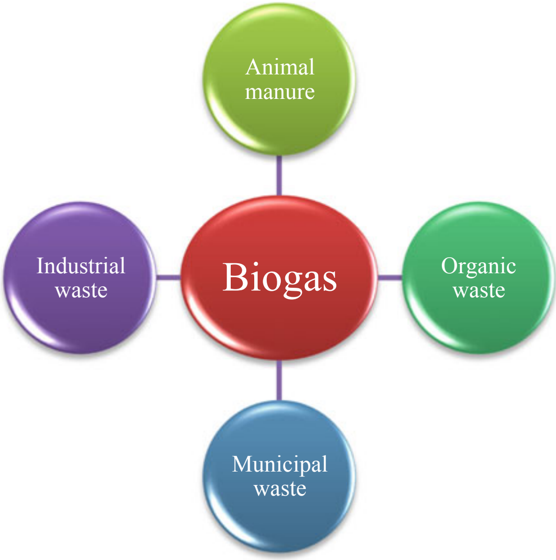


Fig. 4.1 Production of biogas from different types of wastes

organic waste such as manure and industrial and municipal waste. Corn and sugarcane are primarily used for the production of bioethanol (Berghuis et al. 2019).

4.1.3 Biogas

Biogas mainly contains methane and carbon dioxide. Methane forms 40–60% of biogas, and the remaining component is carbon dioxide and traces of water vapors. Biogas can be used as fuel for vehicles if compressed. Biogas could be a suitable replacement for natural gas if it is cleaned and standardized up to natural gas. It is then called biomethane, which could be used as a replacement for methane for cooking and heating purposes. Biogas can be produced by anaerobic digestion from food scraps, animal manure, sewage, and wastewater. Typically, biogas contains 50–75% methane, has a deep blue flame, and could be a good energy source (Fig. 4.1, Table 4.1).

4.1.4 Uses of Biogas

Properly cleaned and upgraded to the standard of natural gas, biogas can be used as a replacement of methane gas for cooking and heating purposes.

Table 4.1 Biogas composition

Components	Percentage (%)
Methane (CH_4)	50–80
Carbon dioxide (CO_2)	20–50
Nitrogen (N_2)	< 1
Hydrogen (H_2)	< 1
Ammonia (NH_4)	< 1
Hydrogen sulfide (H_2S)	< 1

- Compressed biogas can be used as a replacement for compressed natural gas for vehicles.
- Biogas is used for electricity production and water heating, etc.
- Biogas is used to displace CO_2 in combined heat and power (CHP) plants (Boll et al. 2020; Liu et al. 2018a, b).

4.2 Feedstocks for Anaerobic Digestion

The most readily biodegradable organic materials are accepted as feedstocks for anaerobic digestion. Commonly used feedstocks include waste from food processing, sewage sludge, and livestock manure. Feedstocks possess a high potential for energy production, which depends on the level, type of processing, and concentration of the biodegradable material. Feedstock includes any kind of "bio" option, including crop residues, energy crops, plant oils, and waste streams like a municipal waste comprise of production, harvesting, storage, and transportation costs (Tilley et al. 2014).

4.2.1 Types of Feedstocks

- Agricultural residues include all kinds of agricultural waste, such as bagasse, straw, stems, stalks, leaves, husks, shells, pulp, peels, etc., (Fig. 4.2)
- Animal waste, such as manure, is a suitable source for producing energy
- Industrial wastes

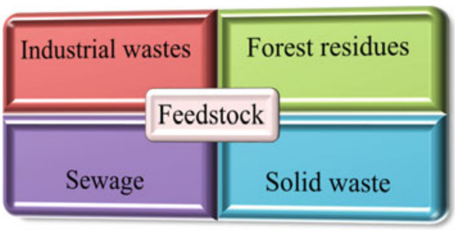


Fig. 4.2 Types of feedstocks

- Forest residues
- Solid waste
- Sewage.

4.2.2 Feedstock for Biomass

Renewable resources of biomass can be used directly as a fuel, or it can be converted to any other form of energy products that are commonly termed feedstocks (Table 4.2).

4.2.2.1 Biomass Feedstocks

Biomass feedstocks mainly include residues of crops, dedicated energy crops, algae, forestry residues, wood processing, municipal solid waste, and waste of urban wood (Fig. 4.3).

4.2.2.2 Dedicated Energy Crops

Non-food crops grown on land unsuitable for the commonly cultivated crops like rice, wheat, and corn to produce biomass are called dedicated energy crops. These crops are generally divided into two categories herbs and woody plants. Herbs are perennial and harvested annually; it takes 2–3 years to give maximum productivity. These crops include miscanthus, bamboo, tall fescue, sweet sorghum, Kochia, wheatgrass, and switchgrass. Short rotation woody crops are harvested after 5–8 years of their plantation. These woody trees include hybrid willow, poplar, eastern cottonwood, silver maple, green ash, sycamore, sweetgum, and black walnut. These species aid in improving soil and water quality, habitat for wildlife-related agricultural crops, diversifying the income source, and enhancing farm productivity (Benner 1989).

Table 4.2 Types of biomass feedstock

Biomass type	Examples
Forests stuffs	Sawdust, bark, wood, shrubs residues
Bio renewable energy wastes	Crop residues, agricultural wastes, urban wood wastes, mill wood wastes
Organic wastes	Industrial wastes, municipal wastes, municipal sewage, and sludge
Lichens	Crustose, foliose and fruticose lichens
Mosses	Polytrichales, Bryophyta
Algae	Prokaryotic, eukaryotic algae, and kelps

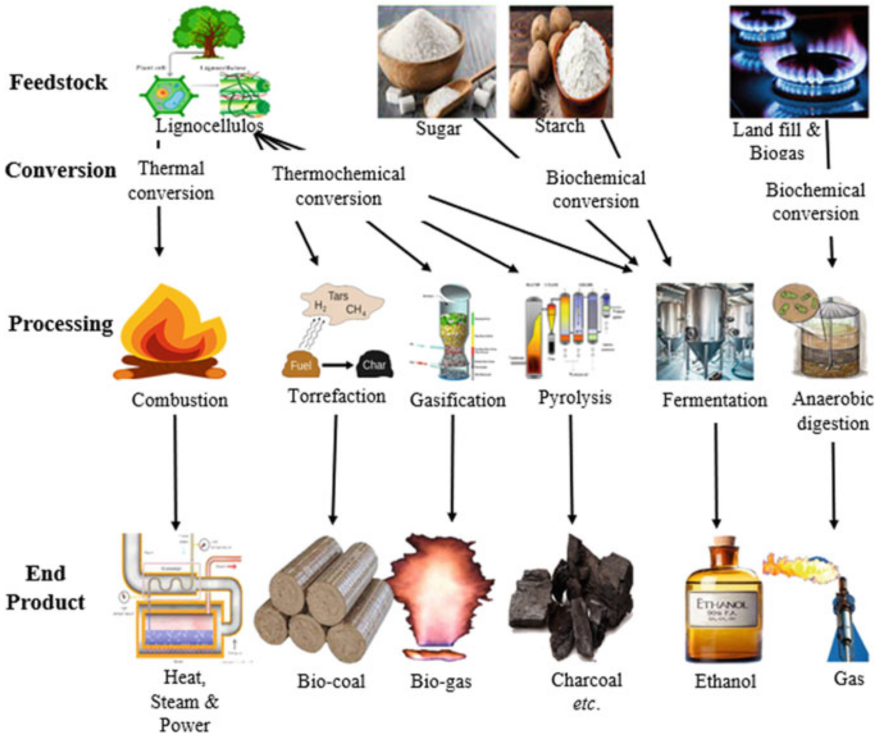


Fig. 4.3 Applications of biomass

4.2.2.3 Agricultural Crop Residue

On existing lands, there are numerous opportunities to maximize agricultural resources without compromising the production of feed, food, and fiber. It includes leaves and stalks that are abundant and widely distributed worldwide. Major residue crops include wheat straw, corn stover, oat straw, rice straw, barley straw, and sorghum stubble. These residues can be sold to the local refineries, which create an additional income source for the farmers.

4.2.2.4 Forestry Residues

Forest residues left over from the logging of timber or whole-tree biomass specifically harvested for biomass make up the two main types of forest biomass feedstocks. After logging, dead, diseased and other unsaleable trees are frequently left in the forest.

The woody waste is collected for bioenergy production with left over waste material to nourish habitat and support nutritional and hydrologic aspects. Additionally, surplus biomass can be used on millions of vast acres of forestland. In addition, forest vitality, restoration, resilience, productivity, and overharvesting of woody biomass will lessen pest infestation. Without harming the health and stability of the forest's biological structure and function, the biomass might be collected for bioenergy production (Niu et al. 2013; Svoboda and Carcluie 2003; Zhao et al. 2018).

4.2.2.5 Algae

Algae as feedstock for bioenergy generally refers to various highly productive species, such as macroalgae, microalgae, and cyanobacteria. Algae use sunlight to produce biomass, which has all necessary elements such as lipids, carbohydrates, and proteins, which can be converted into biofuels and other bioenergy products. Depending on the type of strain, algae can possibly grow in salty, fresh, or brackish water. They can also flourish in water from second-use sources, including the production of water from the operations of oil and gas drilling, municipal, industrial wastewater, aquaculture, agricultural, or wastewater.

4.2.2.6 Wood Processing Residues

Waste streams and by-products from wood processing are referred to as wood processing residues and possess a large amount of energy potential. Such as in wood processing for pulp or other products that produces bark, sawdust, branches, and needles/leaves. Bioproducts or biofuels can be formed by converting these residues as these residues are the waste of wood processing and prove to be an inexpensive and convenient source for biomass production.

4.2.2.7 Sorted Municipal Waste

MSW includes yard trimmings, paperboard, plastics, paper, rubber, food, textiles, and leather wastes are examples of mixed residential and commercial waste. MSW is used for bioenergy production by redirecting substantial amounts of MSW from landfills to the refinery. It also provides an opportunity to lower household and commercial waste.

4.2.2.8 Wet Waste

Institutional, Residential, and Commercial food wastes, organically rich biosolids, manure slurries, organic wastes of industries, and biogas produced from any of the aforementioned feedstock streams are examples of wet waste feedstocks. Rural economies can generate more income, and trash-disposal issues can be resolved by turning these "waste streams" into biofuels (Bastian et al. 2009; Beale et al. 2016; Stowhas et al. 2018).

4.2.3 Feedstock for Biofuel

A sustainable fuel known as biodiesel is created from various feedstocks, such as animal fats, cooking oils, and vegetable oils. Biodiesel produced by different feedstocks possesses different qualities, which should be considered before mixing biodiesel with petroleum diesel (Bertucci et al. 2019).

4.2.4 Chemical Feedstock

A feedstock is sometimes referred to as a raw material or an unprocessed substance. It is an alternative term for biomass which is used to produce or process other products. In carbon-based chemical industries, natural gas, and crude oil accounted for 87% of feedstocks in 2016. During utilization and manufacturing, carbon dioxide is emitted.

Examples of feedstock include crude oil, which is utilized in the production of gasoline, corn, which is utilized in the production of soybean oil and ethanol, which is used in the production of biodiesel (Bharagava et al. 2019; Bingol et al. 2015).

4.3 Best Feedstock for Anaerobic Digestion

- Crops, sewage, slurries, and plant waste are all examples of biodegradable material that can be utilized as fuel for anaerobic digestion. Animal manures
- Spent feed
- Waste products from the food industry
- Waste from slaughterhouses
- Farm fatalities
- Corn silage
- Glycerin; a byproduct for the manufacturing of biodiesel.

4.3.1 Biodegradable Biomass Materials

Biodegradable waste is a waste that can be broken down by other living organisms and often comes from botanical and animal sources. Wastes are considered non-biodegradable if other living things cannot break them down. Biodegradable plastic, green garbage, food, and paper waste are all examples of biodegradable waste frequently found in municipal solid waste also known as BMW (biodegradable municipal waste) (Campanaro et al. 2016, 2019; Cardinali-Rezende et al. 2016).

Following are some biodegradable wastes

- Food waste
- Human feces
- Paper scraps
- Manure
- Sewage
- Medical waste
- Sludge from sewage
- Waste from slaughterhouses.

4.4 Benefits of Anaerobic Digestion

Anaerobic digestion is exciting because it is a streamlined and natural approach to convert a wide range of complex waste into nature friendly fuel gas. There are certain advantages and disadvantages which are summarized in Table 4.3.

There are two main benefits of anaerobic digestion (Fig. 4.3).

- Environmental Benefits
- Economic Benefits.

4.4.1 Environmental Benefits

The natural environment provides many benefits that are difficult to quantify in monetary terms. Natural process assist in reducing greenhouse gas emission, cleaning the air we breathe, clean the water we drink, create food and medicines, decrease noise and chemical pollution, slow floods, and calm streets. This is referred as "ecosystem services" (Date et al. 2012; De Vrieze et al. 2017, 2016).

Table 4.3 Advantages and disadvantages of anaerobic digestion in developing countries

Advantages	Disadvantages
Low construction cost	Susceptibility to mechanical damage
Low sludge production	Lack of locally available materials
Ease of transportation	Low gas pressure requires extra weight
Higher digester temperatures in warm climates	Scum cannot be removed from digester
Easy emptying and maintenance	Used as a pre-treatment stage
Low nutrient (phosphorus and nitrogen) requirements	Need high temperature for effective operation
Use of solid and liquid residues as solid conditioner	Requires monitoring for smooth operation

Anaerobic digestion of organic matter will reduces the organic matter load and associated oxygen demand on manure handling process. This will results in processed components to be more ecofriendly and smaller with less harmful environmental effects. Compared to mechanical aeration, anaerobic pre-treatment being an economical method by converting an anaerobic lagoon to an aerobic lagoon. Digested elute is more operational than raw manure due to the presence of more stable organic load with less volatile odorants.

4.4.2 Economic Benefits

Economic advantages of anaerobic digestion are measured in terms of increased productivity and yield. Recycled nutrients will produce an ecofriendly and sustainable food products resulting in increased net income and revenues, etc. Additionally, produced heat, fuel, or electricity from biogas will be used on-farm, reducing the dependence of agriculture sector's on fossil fuel energy. It will save money while debating a proposal to cut expenditures. Net income and revenues are two examples of economic benefits, which will be managed wisely by effective operation of anaerobic digestion. Profit and cash flow are economic gains as well. Reducing something, e.g., cost, can be considered an economic benefit. Lowering labor and raw material costs are the economic benefits (Campanaro et al. 2016, 2019; Cardinali-Rezende et al. 2016; Castellano-Hinojosa et al. 2018; Chaleckis et al. 2019; De Vrieze, Pinto, et al. 2018a, b).

4.5 Recent Trends in Anaerobic Digestion Technology

Environmental studies for producing biogas to reduce greenhouse gas emissions, focusing on the engineering and microbiological factors involved, have been the most popular topics in the field throughout the past five years of publications. Integrating feedstock pre-treatment with the core processing of the substrates by AD to improve biogas quality and production is the key trend and opportunity. One alternative to achieve the appropriate Sustainable Development Goals is to produce biofuels and bioenergy using AD methods. Finally, understanding feedstock pre-treatment concerning process modeling, optimization, and operation is essential to establishing AD as a successful management system that reaps benefits for both the environment and the economy (De Vrieze, Ijaz, et al. 2018a, b; DeLong et al. 1989; Dione et al. 2016).

4.5.1 Development of Anaerobic Digestion Units

Anaerobic digestion is broken down into four main phases: acidogenesis, hydrolysis, methanogenesis, and acetogenesis. The whole process can be represented by the chemical reaction, in which anaerobic microbes biochemically eat organic material like glucose to produce methane and carbon dioxide.

Most anaerobic digesters use heat exchangers (HXs), which don't mix the liquids as they transport heat from hot water to sludge. A boiler or combined power and heat engine is used to heat the water. The latter process, also referred to as cogeneration, converts biogas into renewable electrical energy (Fang 2010; Ferguson et al. 2016).

4.6 Anaerobic Digestion System and Its Economic Analysis

Even though, the anaerobic digestion of modest amounts of food and organic waste was once thought unprofitable, it is now expanding because of a novel method of producing biogas: small-scale digestion facilities. One hundred thirty micro-scale digestion units were running throughout Europe as of 2016. These manufacturing units, which are smaller, less expensive, and more easily self-sufficient, draw farmers and investors in eco-neighborhoods who want to create new clean energy sources (Martin Alexander Fischer et al. 2019a, b; Martin A Fischer et al. 2019a, b; Franke-Whittle, Goberna, and Insam 2009a, b; Franke-Whittle, Goberna, Pfister, et al. 2009a, b).

4.6.1 Small to Large-Scale Digestion System

Biogas is produced on a small scale in a farm or small community by micro-scale digestion. The production units for small-scale digestion are under 80 kW. While some industrial units have a power capacity of over 1000 kW, most agricultural units are between 100 and 300 kW. Starting with 100 dairy cows, 200 cows, or between 200 and 5000 tons of organic waste per year, a small-scale digestion operation is carried out. Micro-scale digestion enables the system's independence by supplying the digester with agricultural products, which is the attraction of small-scale digestion because it avoids the need to invest in huge facilities (Franke-Whittle et al. 2014; Giacomoni et al. 2015; Grohmann et al. 2018).

4.7 Anaerobic Digestion System and Economic Impact

Small-scale digestion is an excellent, reasonably priced solution for farmers to diversify their businesses. After 2010, on-farm micro-scale digesting plants started to develop. For several reasons, agricultural wastes by farmers are well suited to be used for anaerobic digestion (Fig. 4.4). It will

- Generate their heat and electricity, saving money.
- Reduce greenhouse gas emissions associated with livestock waste.
- Lessen the powerful smells connected with using untreated manure as fertilizer.
- Reduce the distance that organic inputs must be transported to on-site facilities for treatment.
- Take advantage of the digestate's benefits, such as more liquid material that is simpler to distribute, fewer weeds, mineralized nitrogen, etc.

4.7.1 Small-Scale Anaerobic Digestion System and Its Economic Benefits

Israel-based home biogas has created an anaerobic digester for residential use. It uses food waste to generate biogas and fertilizer. It requires six liters of food waste per day to sustain it. Thus, one can use the generated biogas for cooking, lighting, and heating (Gysi et al. 2018; Hagen et al. 2017).

Since 2015, around 1000 family-sized biogas systems have been introduced to over 90 countries. Home biogas systems have already been implemented in several eco-districts in Great Britain. With its ability to digest up to 12 L of kitchen waste and up to 36 L of animal manure, the new model, home biogas 2.0, provides a bigger micro-scale of biogas production. Another example of a micro-technology

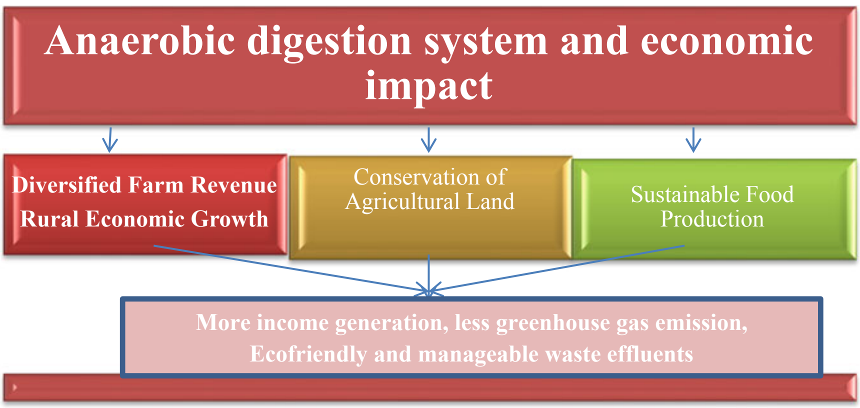


Fig. 4.4 Anaerobic digestion system and economic impact

that aids consumers and businesses in better managing their food waste is the small-scale, fully automated and insulated anaerobic digester offered by MyGug. In home biogas, food waste is converted into biogas and fertilizer. Six liters of food waste per day are needed to feed it. They can hold up to 0.5 tons of food waste annually and come in various sizes suitable for residential or commercial use (Hanreich et al. 2013; Hao et al. 2015; Hassa et al. 2018; Heyer et al. 2015, 2019). The biogas produced can thus be used for cooking, heating, and lighting (Ho et al. 2013; Hori et al. 2014; Iwai et al. 2016; Jia et al. 2019, 2018). Its design explicitly for domestic use,

However, a regulatory framework should be implemented to promote micro-small digestion in cities. Even while the French government continues to support the growth of renewable energies, the legislative framework must permit small-scale digestion facilities in urban areas.

4.7.2 Large-Scale Anaerobic Digestion System and Its Economic Benefits

Large-scale digesters have historically been more common in most developed nations since they require more extensive infrastructure and substantial financial commitment. The biogas that is produced is mostly utilized for heating and power, while it is occasionally upgraded to become a transportation fuel. Europe's two main digester operation modes are "centralized" systems and "farm-scale" digesters. A centralized or combined system codigests agricultural leftovers, food waste, the organic portion of municipal solid waste (MSW), and animal manure from multiple farms. A portion of the digestate is returned to the farms in this model to be utilized as fertilizer, while the remainder is sold to other farms. These centralized facilities have enormous digesters with a capacity of up to 300,000 ft^3 (Jun et al. 2015; Kampmann et al. 2012; Khelaifia et al. 2016; Kim et al. 2017, 2015).

Farm-scale AD facilities are often constructed in big swine or dairy farms, and their digester capacities range from 7000 to 42,000 ft^3. They combine the animal waste from one or more farms with other organic stuff that is readily available, such as the energy crops that were raised on those farms. The AD industry is well-established in the United States and is used to treat sewage sludge in wastewater treatment facilities. There are just 38 industrial AD plants, compared to 1250 wastewater treatment facilities and roughly 250 farm-scale anaerobic digesters (Kirkegaard et al. 2017; Kohrs et al. 2014; Lagier et al. 2012; Langer et al. 2015; Langille et al. 2013).

In the past ten years, around 90% of the AD plants have been built, and 86% use dairy manure as their primary feedstock. According to USDA, U.S. EPA, and U.S. DOE, there is a significant opportunity for the AD business to expand in the United States, with the ability to use the manure from 8000 dairy and swine farms to produce enough energy to power 1.09 million homes (Li et al. 2015, 2017; Limam et al. 2014; Lu et al. 2013). Additionally, almost 2500 wastewater treatment facilities have the capacity to make biogas, many of which are actively producing methane but not using it (Lü et al. 2014; Lv et al. 2010).

Large-scale AD systems use a variety of feedstocks, including waste from agricultural or livestock farms, food waste, and wastewater/sewage sludge, and require considerable capital investment and upkeep. The economics of such plants vary widely because of the nature of these systems. The primary source of production costs for AD systems is capital expenditures. Operating costs range from $18 to $100 per ton of feedstock handled by the facility, depending on the size of the AD plant. According to a survey of 38 AD systems in the United States, the equipment used to generate energy accounts for about 36% of the entire capital expense. The price ($/kWh) for producing energy at AD plants ranges from $0.06 to $0.23. The AD plant and the fuel influence the cost of producing energy. Due to economies of scale, electricity generation costs are often lower for higher plant sizes (Manor and Borenstein 2017; Marchand et al. 2017; Maus et al. 2016).

4.8 Conclusion and Future Prospects

Due to the production of biogas and its various uses, additional products (such as digestate that could be used as biofertilizer), the collection of dumping fees, and government subsidies, AD has several economic advantages. AD has gained popularity worldwide, from modest household digesters in impoverished rural countries to expansive systems in wealthy nations. The primary cost factor for AD plants is capital expenditures. The choice and accessibility of the feedstock are vital factors in the economics of large-scale systems. Although prices have stabilized in Asia, where the technology has been in use for a more extended period of time, small-scale digesters' capital costs vary significantly in countries where their introduction is relatively recent. Future technological developments in digestate management and biogas utilization may improve the economics of AD plants.

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