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Flexible Biogas Technology: Design Strategies, Operational Challenges, and Pathways Ahead

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Abstract

Anaerobic digestion is an established technology for converting biodegradable organic wastes into renewable biogas and nutrient-rich digestate. Flexible biogas plants have emerged as an alternative to conventional fixed-dome and floating-drum digesters, particularly for decentralized and rural applications, because of their simplified construction, reduced permanent infrastructure requirements, portability and adaptability. However, the performance and long-term applicability of flexible systems depend on feedstock characteristics, digester configuration and operating conditions. This review critically examines the development and current status of flexible biogas plants, covering their construction, components, working principle, configurations and major advantages and limitations. The review also discusses the suitability of different organic feedstocks, co-digestion strategies and the stages of anaerobic digestion, followed by an assessment of key operating parameters including temperature, pH, total solids, volatile solids, organic loading rate, hydraulic retention time, mixing and feeding conditions. Performance is evaluated using biogas production, specific gas yield, methane content, seasonal response and operational reliability. Economic aspects, including investment and operating costs, energy substitution, digestate utilization and financial indicators, are also considered. The environmental significance of flexible systems is discussed in relation to organic waste management, methane recovery, renewable energy production and nutrient recycling. Major challenges include membrane durability, leakage, temperature sensitivity, gas-pressure management, feedstock availability and limited technical support. The review identifies key research needs in long-term durability, seasonal performance, capacity-based comparison, standardized performance evaluation, economic assessment, digestate utilization and low-cost monitoring. Future development should focus on durable materials, improved system reliability, simple monitoring and adaptable decentralized configurations. Overall, flexible biogas plants show considerable potential for integrated organic waste management, renewable energy generation and nutrient recovery, provided that long-term technical and operational limitations are adequately addressed.

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1. Introduction

Biogas is a renewable energy source produced through the anaerobic digestion of biodegradable organic matter under oxygen-free conditions. The process converts organic substrates into biogas and produces digested slurry that can be utilized for nutrient recycling. Biogas therefore provides a combined pathway for renewable energy generation, organic-waste management and recovery of agricultural nutrients, with applications including cooking, heating and electricity generation^[1,2].

The availability of organic residues from agriculture, livestock production, households and food-related activities provides a substantial resource for biogas production. The International Energy Agency has highlighted the potential of biogas and biomethane as renewable sources of heat, power and clean cooking energy, particularly when wastes and residues are used as feedstocks^[1]. In India, biogas development has been supported through national programmes and waste-to-energy initiatives aimed at improving the utilization of organic wastes and producing renewable energy and organic manure^[2].

Different biogas-plant configurations have been developed according to feedstock availability, capacity, climatic conditions, construction practices and operational requirements.

Fixed-dome systems, including Janata and Deenbandhu models, and floating-drum systems such as the KVIC model are established technologies for household and small-scale applications. The selection of a suitable plant depends on factors including reliability, safety, maintainability, construction requirements and overall system performance^[3]. Flexible biogas plants provide an alternative configuration in which flexible material is used for digestion and/or gas storage. Compared with conventional masonry systems, these plants can reduce permanent civil construction requirements and facilitate installation in locations where conventional digesters are difficult to construct. Mungwe *et al.* identified digester volume, gas-storage volume, installation-pit volume, total solids, organic loading rate, and temperature and slurry pH as important considerations in the design and operation of flexible digesters^[4].

The performance of flexible biogas plants depends on the interaction of feedstock characteristics, digester design and operating conditions. Biogas production rate, productivity, gas quality and biodegradation are important performance indicators, while parameters such as temperature, pH, organic loading rate, solids concentration and hydraulic retention time influence digestion stability and gas production^[4,5]. Although flexible systems offer advantages in portability and simplified installation, their wider application is influenced by membrane durability, leakage, gas-pressure management, seasonal temperature variation, feedstock availability and maintenance requirements^[4,5].

Despite the growing application of anaerobic digestion, literature specifically addressing flexible biogas plants remains distributed among studies on plant design, feedstocks, operating conditions, performance, economics and field applications. A consolidated assessment is therefore required to understand the development of flexible systems, their operating performance, advantages and limitations, and the factors controlling their long-term applicability.

The present review critically examines flexible biogas plants with emphasis on their evolution, construction, working principle, feedstocks, anaerobic digestion process, operating parameters, performance, economic feasibility, environmental

benefits, challenges and future prospects. Particular attention is given to seasonal performance, material durability, optimization, economic assessment and long-term operation, which are important for the wider adoption of flexible biogas technology.

2. Evolution of Biogas Technology

The development of biogas technology has progressed through different digester configurations aimed at improving gas storage, pressure regulation, construction requirements, durability and ease of operation. For household and small-scale applications, fixed-dome, floating-drum, tubular and flexible-bag systems represent important stages in this development, while two-stage configurations have subsequently been investigated for improved process control^[3,5].

2.1 Fixed-Dome Biogas Plants

Fixed-dome plants are among the established designs for household biogas production. The digester and gas-storage dome form a stationary enclosed structure, generally constructed below ground. As biogas accumulates in the dome, the resulting pressure displaces slurry towards the outlet. The underground structure provides physical protection and can moderate external temperature fluctuations^[3].

In India, the Janata and Deenbandhu models are important examples of fixed-dome plants. The Deenbandhu design was developed to reduce construction material requirements compared with earlier designs while maintaining the basic fixed-dome principle. Fixed-dome plants have the advantages of a long service life and absence of moving parts, but cracking of masonry can cause gas leakage and repair may require skilled labour^[3].

2.2 Floating-Drum Biogas Plants

Floating-drum plants consist of a fixed digester with a movable gas holder that rises and falls according to the quantity of gas stored. The movement of the drum provides relatively stable gas pressure and gives a visual indication of stored gas^[3,5].

These plants can be operated with animal manure and other organic substrates, although fibrous materials may interfere with movement of the gas holder. A major limitation is corrosion of metallic gas holders, which increases maintenance requirements and can reduce long-term economic attractiveness^[3].

2.3 Tubular and Flexible-Bag Digesters

The development of tubular and flexible-bag digesters represented a shift from permanent masonry and metallic structures towards lightweight polymeric systems. Tubular digesters generally consist of a flexible chamber with inlet and outlet arrangements through which feed enters and digested slurry is displaced. Their simple construction requires less permanent civil work and facilitates transportation and installation in rural and decentralized locations^[4,5]. Flexible-bag or balloon systems store the digestion slurry and biogas within a flexible polymeric structure. Additional weight may be applied over the gas-storage section to obtain the pressure required for gas utilization. These systems became attractive because of their relatively simple installation, portability and lower construction requirements compared with conventional digesters^[3,4].

The development of flexible systems subsequently moved towards more standardized and prefabricated designs incorporating defined digestion and gas-storage sections, feeding arrangements, gas pipelines and pressure-control components. Commercial systems such as HomeBiogas illustrate this transition from simple flexible bags towards integrated household-scale systems [4,6].

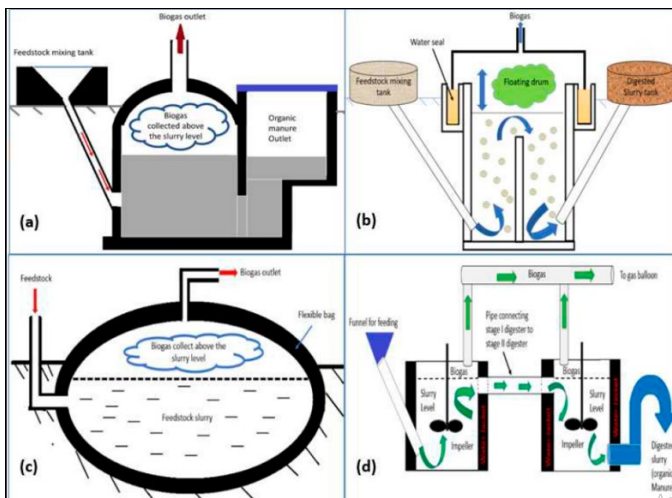


Fig 1: “Different types of biogas plants used for domestic biogas plants: (a) Fixed-type, (b) Floating-type, (c) Balloon-type and (d) Two-stage biogas plant” [3]

2.4 Evolution towards Flexible and Specialized Systems

The transition from fixed-dome and floating-drum plants towards tubular and flexible systems has mainly been driven by the need for lower construction requirements, portability and adaptability to decentralized applications. Flexible systems can be manufactured and transported as prefabricated units and can be adapted to different capacities and local feedstock conditions [4,5].

However, the development of flexible plants has also highlighted limitations associated with polymeric materials and gas storage. Shorter service life, leakage, low or variable gas pressure, temperature sensitivity and mechanical damage have been reported as important considerations. Comparative evaluation of different plant configurations has indicated that balloon-type systems may have lower long-term performability than fixed-dome systems, particularly with respect to durability and reliability [3].

Two-stage digestion represents another direction in the development of biogas technology. Instead of carrying out the major biological stages within a single reactor, the process can be separated into different stages to provide greater control over digestion. Although this configuration may improve process performance under suitable conditions, additional components can increase capital, operation and maintenance requirements [3].

Overall, the evolution of biogas plants reflects a progression from permanent conventional structures towards systems offering greater flexibility, portability and simplified installation. For flexible plants, however, improved durability, pressure management and protection from environmental conditions remain essential for achieving reliable long-term operation.

3. Flexible Biogas Plants

Flexible biogas plants are anaerobic digestion systems in which flexible polymeric materials are used to form the digestion chamber and/or gas-storage section. Compared with conventional fixed-dome and floating-drum plants, these systems require less permanent civil construction and can be manufactured as prefabricated units. Their design is particularly relevant to decentralized and rural applications where transportation, construction resources and installation conditions can limit the use of conventional digesters [4,18].

3.1 Construction and Components

A flexible biogas plant generally consists of a flexible digester, gas-storage section, inlet, outlet, gas pipeline, valves and supporting arrangements. Polymeric materials are commonly used for the flexible structure, while PVC pipes may be used for inlet and outlet connections. The digester provides the anaerobic environment for microbial conversion of organic matter, whereas the gas-storage section collects the produced biogas for subsequent utilization [4].

The inlet and outlet provide feeding and slurry-displacement arrangements, while the gas pipeline connects the storage section to the point of use. Pressure-control and safety arrangements may also be incorporated to manage gas pressure. Commercial systems such as Home Biogas use defined digestion and gas-storage compartments with prefabricated components, illustrating the development of flexible plants from simple bag digesters towards standardized household systems [4,6].

Material selection is important because the flexible structure is exposed to both the digestion environment and external conditions. Multilayer polymeric materials and protective outer layers can be used to improve resistance to mechanical and environmental stresses [6].

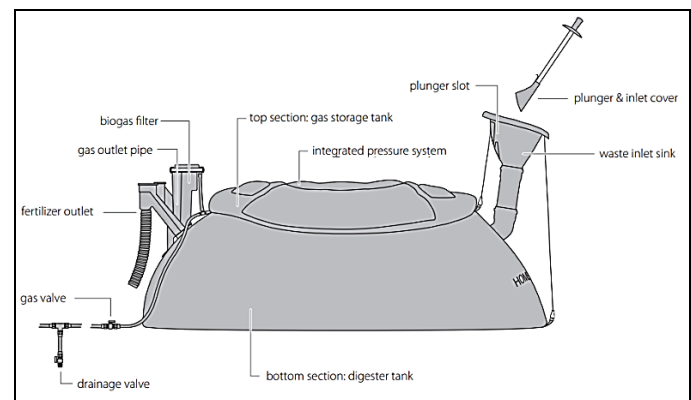


Fig 2: General Layout of Homebiogas2.0 (HBG2.0)[6]

3.2 Working Principle

The operation of a flexible biogas plant is based on anaerobic digestion of biodegradable feedstock in a sealed chamber. Prepared organic material is introduced through the inlet, where microorganisms degrade the substrate under oxygen-free conditions and produce biogas. The gas accumulates in the flexible storage section, while the entry of fresh feed displaces an approximately equivalent quantity of digested slurry through the outlet [4].

Stored biogas is conveyed through the gas pipeline for cooking or other energy applications. In some flexible systems, external loading is applied to the gas-storage section to provide sufficient pressure for gas delivery [6]. The overall operation can therefore be represented as:

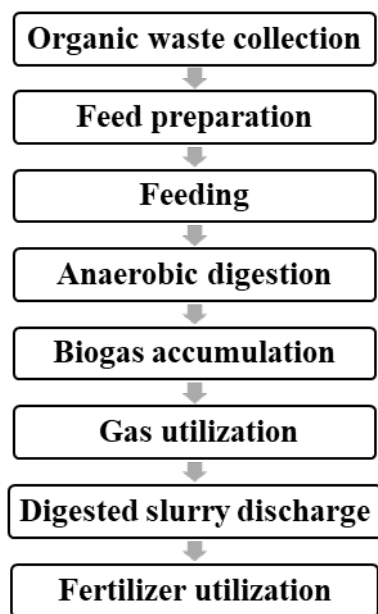


Fig 3: Working principle of a flexible biogas plant

The quantity and rate of biogas production depend on feedstock characteristics and operating conditions within the digester [4,7].

3.3 Types and Configurations of Flexible Biogas Plants

Flexible biogas plants include several configurations according to capacity, feedstock and installation conditions. Flexible-bag or balloon digesters use a flexible structure for digestion and gas storage and are generally suitable for small-scale applications. Tubular digesters use an elongated flexible chamber with inlet and outlet arrangements at opposite ends and are commonly considered for rural and decentralized applications [4,5].

Prefabricated commercial systems represent a more standardized form of flexible technology. HomeBiogas 2.0, for example, incorporates separate digestion and gas-storage sections together with defined feeding, outlet and gas-conveying components [6]. Flexible plants may also be supported within an installation pit, which provides physical support and helps maintain the required configuration during operation [4].

Table 1: Major configurations of flexible biogas plants

Configuration	Main feature	Typical application
Flexible-bag/balloon	Flexible structure for digestion and gas storage	Household and small-scale systems
Tubular digester	Elongated flexible digestion chamber	Rural and decentralized applications
Prefabricated flexible system	Standardized digester, gas-storage section and accessories	Household/institutional applications
Pit-supported flexible digester	Flexible structure supported by an installation pit	Rural and semi-permanent installations

Source: Compiled from Mungwe *et al.* [4], Rajendran *et al.* [5] and Gautam and Jha [6].

3.4 Advantages of Flexible Biogas Plants

The principal advantages of flexible biogas plants are reduced civil construction, rapid installation, lightweight construction and portability. These characteristics can be particularly beneficial in rural and remote locations where conventional construction materials and skilled labour are difficult to obtain. Flexible systems can also be adapted to different feedstocks and capacities and may require lower initial infrastructure investment than permanent digesters [4,18].

However, flexible systems have important limitations. Membrane durability, leakage, mechanical damage and gas-pressure management can influence long-term reliability. Their performance may also be more sensitive to environmental temperature variations than underground masonry systems. Proper installation, protection of the flexible structure and control of feed characteristics are therefore important for reliable operation [3,4].

Table 2: Advantages and limitations of flexible biogas plants

Advantages	Limitations
Low requirement for civil construction	Membrane durability concerns
Rapid and relatively simple installation	Leakage and mechanical damage
Lightweight and portable	Temperature sensitivity
Suitable for rural and remote areas	Proper feeding and loading required
Adaptable to different feedstocks and capacities	Performance depends on operating conditions
Potentially lower initial infrastructure cost	Service life may be lower for some systems

Source: Compiled from Mungwe *et al.* [4], Gautam and Jha [6] and Pradhan *et al.* [18].

Flexible biogas plants therefore provide a practical alternative to permanent digesters where portability, simplified installation and reduced construction requirements are important. Their wider adoption, however, depends on improving material durability, preventing leakage, maintaining suitable gas pressure and ensuring stable operation under varying environmental conditions [3,4].

4. Feedstocks Used in Flexible Biogas Plants

Feedstock selection is an important factor in the design and operation of flexible biogas plants because substrate characteristics influence biogas production, methane yield and process stability. Common substrates include animal manure, kitchen and food waste, vegetable and fruit waste, agricultural residues and mixtures of different organic materials. Their suitability depends on characteristics such as moisture content, total and volatile solids, biodegradability, nutrient composition, particle size and carbon-to-nitrogen ratio [7,9].

Feedstock availability is also important for decentralized flexible systems. Animal manure is commonly available in livestock-producing rural areas, while kitchen and food wastes are continuously generated by households, institutions and food-related activities. Agricultural residues are available in large quantities but may show considerable seasonal variation. Therefore, feedstock selection should consider both its biogas-producing potential and its regular local availability [7].

4.1 Major Feedstocks

Animal manure: Cattle dung, pig manure and poultry manure are important substrates for small-scale anaerobic digestion. Cattle dung is particularly suitable for decentralized plants

because of its availability and relatively stable digestion characteristics. It can also serve as a base substrate for co-digestion with more readily degradable wastes. Pig manure provides biodegradable organic matter, whereas poultry manure requires attention to nitrogen loading and possible ammonia accumulation [7].

Kitchen and food waste: Kitchen and food wastes are highly biodegradable substrates with considerable biogas potential. Their composition can vary according to source and may include cooked food, vegetables, fruits, cereals and other organic materials. Because rapid degradation can occur, excessive loading may disturb process stability; therefore, feeding rate and substrate preparation should be matched with digester capacity [9].

Fruit and vegetable waste: Fruit and vegetable wastes generally have high moisture content and readily biodegradable organic matter. Gupta *et al.* reported variations in moisture, volatile matter, ash and fixed carbon among vegetable and fruit wastes collected from a market, demonstrating the variability of such substrates [10]. Their high moisture content can reduce the need for additional dilution, although gas yield should preferably be evaluated on an organic- or volatile-solids basis rather than fresh mass alone.

Agricultural residues: Crop residues such as straw, grasses and other plant materials represent a large renewable resource but are generally more difficult to digest because of their lignocellulosic structure. Their biodegradability can be improved through size reduction or suitable pretreatment, while co-digestion with animal manure can provide a more suitable substrate combination [7] pretreatment, while co-digestion with animal manure can provide a more suitable substrate combination [7].

4.2 Co-digestion

Co-digestion involves the simultaneous anaerobic digestion of two or more substrates and can help overcome limitations related to nutrient balance, moisture, biodegradability and feedstock availability. Combining cattle dung with kitchen or food waste is particularly relevant to decentralized flexible systems because the substrates can provide complementary characteristics [7].

Ojewumi *et al.* reported that the proportion of cow dung and organic kitchen waste affected biogas yield and methane content [11]. Similarly, San *et al.* demonstrated differences in biogas production when cow dung, pig dung and vegetable waste were combined in different substrate combinations [12]. The optimum mixing ratio is therefore not universal and depends on substrate characteristics and operating conditions.

4.3 Feedstock Characteristics Affecting Digestion

The principal feedstock characteristics influencing anaerobic digestion are moisture content, total solids, volatile solids, ash content, particle size, nutrient composition and C/N ratio [7]. Moisture affects slurry preparation and microbial transport, while total and volatile solids indicate the amount of organic material available for digestion. Higher volatile-solids content generally represents greater potential for biogas production, although actual methane yield also depends on substrate biodegradability and process conditions.

The C/N ratio is particularly important because carbon provides an energy source for microorganisms while nitrogen supports microbial growth. An approximate C/N ratio of 25–30:1 has been reported as suitable for anaerobic digestion [7]. Feedstocks with unsuitable characteristics can therefore be combined through co-digestion to obtain a more favourable substrate composition.

Table 3: Major feedstocks used in flexible biogas systems

Feedstock	Key characteristics	Main potential/consideration
Cow dung	Moist, biodegradable and widely available	Stable household substrate; suitable for co-digestion
Pig manure	Biodegradable organic matter	Good biogas potential
Poultry manure	Nutrient- and nitrogen-rich	Ammonia accumulation requires attention
Kitchen waste	Moisture-rich and highly biodegradable	High biogas potential; loading control required
Food waste	High biodegradable organic fraction	High methane potential; segregation required
Fruit and vegetable waste	High moisture and readily degradable matter	Suitable for market/institutional waste
Agricultural residues	Cellulose- and hemicellulose-rich	Large resource; pretreatment may be required

Source: Ward *et al.* [7], Pathak *et al.* [9], Gupta *et al.* [10], Ojewumi *et al.* [11] and San *et al.* [12].

The available literature indicates that no single feedstock is universally optimal for flexible biogas plants. Animal manure provides a relatively stable and locally available substrate, kitchen and food wastes offer highly biodegradable organic matter, and agricultural residues provide a large but more difficult-to-digest resource. Co-digestion can combine complementary characteristics and improve the suitability of available wastes for anaerobic digestion [7,11]. Feedstock selection should therefore consider substrate characteristics, local availability, seasonal variation and compatibility with the capacity and operating conditions of the flexible plant.

5. Anaerobic Digestion Process

Anaerobic digestion (AD) is a biological process in which biodegradable organic matter is converted by microorganisms under oxygen-free conditions into biogas and digested slurry. The conversion occurs through four interdependent stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis [5,17].

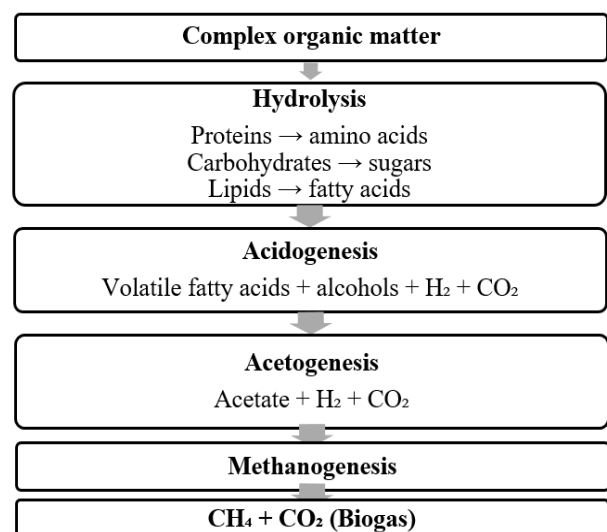


Fig 4: Four major stages of anaerobic digestion

5.1 Hydrolysis and Acidogenesis

Hydrolysis is the initial stage in which complex organic polymers such as carbohydrates, proteins and lipids are converted into soluble compounds, including sugars, amino

acids and fatty acids. These products are subsequently metabolized during acidogenesis to produce volatile fatty acids (VFAs), alcohols, hydrogen and carbon dioxide [5]. The rate of hydrolysis depends on feedstock characteristics. Easily degradable substrates such as kitchen and food waste generally hydrolyse more readily, whereas lignocellulosic agricultural residues are more resistant to microbial degradation. Excessive acid production relative to its subsequent utilization can cause VFA accumulation and a reduction in pH, adversely affecting the later stages of digestion [5,7].

5.2 Acetogenesis and Methanogenesis

During acetogenesis, intermediate products formed during acidogenesis are converted mainly into acetate, hydrogen and carbon dioxide. These compounds provide substrates for methanogenic microorganisms. Methanogenesis is the final stage, during which methanogens convert acetate and hydrogen/carbon dioxide into methane, producing the combustible fraction of biogas [5,17].

Methanogens are sensitive to changes in environmental conditions, particularly pH and temperature. Consequently, imbalance between the different microbial groups can result in intermediate accumulation and reduced methane production [5].

5.3 Microbial Interactions and Biogas Formation

Anaerobic digestion involves a consortium of microorganisms whose activities are sequentially connected. Hydrolytic and fermentative microorganisms break down complex substrates, acetogenic microorganisms convert intermediate products, and methanogens complete the conversion to methane-rich biogas [5].

Biogas consists primarily of methane and carbon dioxide, with smaller quantities of other gases. Methane determines its energy value, while the remaining digested slurry retains nutrients and can be used as an organic fertilizer. Thus, AD simultaneously provides renewable energy and a pathway for nutrient recovery [17].

5.4 Anaerobic Digestion in Flexible Biogas Plants

The biological pathway of anaerobic digestion remains the same in flexible biogas plants as in conventional digesters. The flexible structure provides a sealed environment for microbial activity, while the gas-storage section collects the biogas produced during digestion [4]. Plant performance therefore depends on maintaining suitable conditions for the microbial stages through appropriate feedstock characteristics, temperature, pH, organic loading rate, solids concentration and hydraulic retention time [4,5].

6. Operating Parameters Affecting Performance

The performance of flexible biogas plants depends on operating conditions that control microbial activity, substrate degradation and biogas production. Temperature, pH, total solids (TS), volatile solids (VS), organic loading rate (OLR), hydraulic retention time (HRT), mixing and feeding conditions are among the principal parameters influencing digestion stability and gas production [4,7]. These parameters are interdependent, and changes in one can affect the response of the others.

6.1 Temperature and pH

Temperature strongly influences microbial growth and the rate of anaerobic digestion. Anaerobic digestion can operate

under psychrophilic, mesophilic and thermophilic conditions, with mesophilic digestion generally occurring around 30–40 °C and thermophilic digestion around 50–60 °C [5,7]. Rajendran *et al.* reported that biogas production increased substantially with increasing temperature between 10 and 25 °C, while methanogenic activity was considerably reduced below approximately 15 °C [5]. Temperature fluctuations are therefore particularly important for flexible digesters exposed to ambient conditions.

Mungwe *et al.* designed a flexible digester for mesophilic operation and suggested installation in an excavated pit to reduce temperature fluctuations [4]. Seasonal temperature variation can consequently influence gas production, particularly during colder periods.

pH is another important indicator of digestion stability. Methanogenic microorganisms generally perform best under near-neutral conditions. Mungwe *et al.* reported an optimum range of approximately 6.5–7.5, while Ward *et al.* identified a narrower range around 6.8–7.2 for methanogenic activity [4,7]. Excessive formation of volatile fatty acids can reduce pH and inhibit methanogenesis; therefore, stable feeding and avoidance of sudden overloading are important for maintaining suitable pH conditions.

6.2 Total Solids and Volatile Solids

Total solids determine the concentration of substrate entering the digester, while volatile solids represent the biodegradable organic fraction of the solids. VS reduction is commonly used as an indicator of substrate degradation and digestion efficiency [4,7]. Excessively dilute feed may reduce the amount of organic matter supplied per unit digester volume, whereas excessive solids concentration can increase slurry viscosity and create handling or mixing difficulties.

Appropriate slurry concentration therefore depends on feedstock characteristics and digester configuration. Preparation and dilution should be adjusted to provide sufficient biodegradable material while maintaining suitable physical conditions for digestion.

6.3 Organic Loading Rate and Hydraulic Retention Time

Organic loading rate (OLR) represents the quantity of organic material supplied per unit digester volume per unit time and is commonly expressed as kg VS m⁻³ day⁻¹. It must be balanced with the ability of the microbial population to degrade the supplied substrate [4,7]. Excessive loading can accelerate acid formation and cause VFA accumulation and pH reduction, whereas very low loading can underutilize digester capacity.

Hydraulic retention time (HRT) represents the average period for which slurry remains in the digester. Adequate HRT is required for microbial degradation and methane formation, while excessively short HRT can result in incomplete digestion and microbial washout [4]. The appropriate HRT depends on temperature, feedstock characteristics, solids concentration and appropriate digester configuration.

6.4 Mixing and Feeding Rate

Mixing improves contact between microorganisms and substrate and can reduce localized solids accumulation. However, many flexible digesters are designed as simple, low-cost systems without mechanical mixing. Natural movement associated with feeding, gas production and slurry displacement may provide some mixing, with the requirement for additional mixing depending on feedstock and solids concentration [7].

Regular feeding is important for maintaining stable digestion. Sudden changes in feed quantity or composition can disturb the balance between acid-producing and methane-producing microorganisms, particularly when highly biodegradable kitchen or food waste is used [4]. Lohith and Math reported higher gas production from kitchen waste, cow dung and poultry waste under conditions of approximately pH 6.9–7.1 and 34–39 °C, demonstrating the interaction between substrate and operating conditions [8].

6.5 Interaction of Operating Parameters

Operating parameters should not be considered independently. Temperature influences microbial growth and reaction rates, OLR controls substrate supply, pH reflects the balance between acid formation and consumption, and HRT determines the time available for substrate degradation [4,5]. For example, increasing OLR may increase biogas production until an optimum is reached, beyond which acid accumulation can reduce pH and methane formation. Similarly, lower temperatures can reduce microbial activity and may require longer retention periods for effective degradation [5,7]. Stable flexible-digester operation therefore requires simultaneous consideration of feedstock, temperature, pH, loading and retention time.

Table 4: Major operating parameters affecting flexible biogas plant performance

Parameter	Main influence	Effect of unsuitable condition
Temperature	Controls microbial activity and reaction rate	Reduced digestion rate or inhibition
pH	Influences methanogenic activity	Acidification and reduced methane production
TS/VS	Determines substrate concentration and biodegradable fraction	Poor handling or reduced gas potential
OLR	Controls substrate supply to the digester	Overloading and acid accumulation
HRT	Provides time for microbial degradation	Incomplete digestion or washout
Mixing	Improves substrate–microorganism contact	Solids accumulation and poor contact
Feeding rate	Maintains regular substrate supply	Process instability due to sudden loading

Compiled from Mungwe *et al.* [4], Ward *et al.* [7] and Rajendran *et al.* [5].

Overall, stable performance of flexible biogas plants requires appropriate control of temperature, pH, substrate concentration, OLR and HRT, together with consistent feeding and adequate substrate–microorganism contact. These parameters provide the operating basis for evaluating biogas production, methane content, and specific gas yield and digestion efficiency in flexible systems.

7. Performance of Flexible Biogas Plants

The performance of a flexible biogas plant can be evaluated from its ability to convert organic substrates into biogas while maintaining stable digestion and reliable gas utilization. Important indicators include daily biogas production, specific gas yield, methane content, volatile-solids reduction, gas pressure and process stability [4,8]. Performance is influenced by feedstock characteristics, operating conditions and digester configuration.

7.1 Biogas Production and Specific Gas Yield

Biogas production varies with feedstock composition,

temperature, pH, organic loading rate, hydraulic retention time and digester configuration [4,7]. Flexible digesters have been operated using cattle dung, kitchen waste, poultry manure and mixed organic wastes, with substantial differences in gas production among substrates [8].

Lohith and Math reported total biogas production of approximately 1.016 m³ from kitchen waste, 2.489 m³ from cow dung and 2.397 m³ from poultry waste under their respective experimental conditions [8]. These results demonstrate that total gas production depends strongly on the quantity and characteristics of the substrate supplied.

Specific gas yield provides a more meaningful basis for comparing feedstocks and systems because it relates gas production to the amount of substrate or volatile solids supplied. Food and kitchen wastes generally contain readily biodegradable organic matter, whereas lignocellulosic residues are more resistant to degradation and may require pretreatment [7,9]. Consequently, differences in specific gas yield should not be attributed to digester configuration alone.

7.2 Methane Content and Biogas Quality

Methane content is an important measure of biogas quality because methane is the principal combustible component. Mungwe *et al.* identified methane percentage as an important Performance parameter for flexible digesters, while actual methane concentration depends on substrate composition and digestion conditions [4].

Gas quality should therefore be evaluated together with gas quantity. A system producing a large volume of biogas may not necessarily provide a greater useful energy output if methane concentration is comparatively low. For flexible plants, methane content, daily gas production and consistency of gas generation provide a more meaningful assessment of energy performance than gas volume alone.

7.3 Seasonal Performance

Seasonal variation is particularly relevant to flexible plants because the flexible structure can be more exposed to ambient temperature changes than underground masonry digesters.

Rajendran *et al.* reported a substantial influence of temperature on biogas production and reduced methanogenic activity at low temperatures [5].

Temperature-related reductions in performance can be moderated through appropriate installation, insulation and protection of the digester. Mungwe *et al.* proposed installation of flexible digesters in excavated pits as one approach for reducing temperature fluctuations [4]. Nevertheless, seasonal effects remain an important consideration when flexible systems are operated in regions with large variations in ambient temperature.

7.4 Comparison with Conventional Digesters

Flexible plants provide advantages in installation, portability and reduced permanent construction requirements, but their performance should be evaluated in combination with durability and operational reliability. Comparative assessments indicate that conventional fixed-dome systems may provide greater structural durability, whereas flexible systems offer greater ease of installation and adaptability [3,4].

The performance comparison should therefore consider both short-term energy production and long-term system reliability. Factors such as membrane service life, leakage, gas-pressure stability, maintenance requirements and seasonal performance can influence the practical suitability of flexible systems even when their biogas production is satisfactory [3,4].

Overall, flexible biogas plants can convert a range of organic wastes into useful renewable energy, but their performance varies with feedstock, operating conditions and environmental exposure. A meaningful assessment should therefore combine gas production, specific gas yield, methane content, substrate degradation, seasonal response and operational reliability rather than relying on a single performance indicator.

8. Economic Analysis

Economic feasibility is an important consideration for the adoption of flexible biogas plants. Although flexible systems can reduce permanent civil-construction requirements, their overall economic performance depends on initial investment, operation and maintenance costs, service life, energy savings and the value of digestate [4,5]. Therefore, economic assessment should consider both the benefits generated during operation and the costs associated with maintaining the system over its useful life.

8.1 Investment and Operation Costs

The initial investment generally includes the digester, inlet and outlet arrangements, gas pipeline, valves, burner, installation and other accessories. Flexible systems can reduce construction-related expenditure because they require less permanent masonry than conventional plants; however, membrane quality, plant capacity and associated components influence the final cost [4,5].

Operation and maintenance costs include feeding, cleaning, minor repairs and replacement of damaged components. Although flexible plants may have simpler construction, membrane inspection, leakage repair and replacement of accessories remain important for long-term operation. Consequently, a low initial cost does not necessarily indicate better economic performance if the system has a short service life or requires frequent replacement.

8.2 Energy and Digestate Benefits

The economic value of biogas is primarily associated with the replacement of conventional cooking or energy sources. The actual saving depends on the quantity of biogas produced, the proportion that can be utilized and the local price of the displaced fuel. Obileke *et al.* reported that biogas from a composite-material digester replaced approximately 33.2% of LPG consumption at the study site, demonstrating the importance of actual gas utilization in determining economic benefits [13].

Digestate provides an additional economic benefit because its nutrient content can reduce expenditure on chemical fertilizers or provide value when used as an organic fertilizer. Studies comparing bioslurry from flexible and fixed-dome systems have also demonstrated differences in nutrient characteristics, indicating that digestate value should be considered in the overall economic assessment [16].

8.3 Payback Period and Financial Indicators

Payback period, net present value (NPV), benefit-cost ratio (B:C) and internal rate of return (IRR) are commonly used to assess the financial feasibility of biogas projects. Payback period indicates the time required to recover the initial investment, while NPV considers the present value of future costs and benefits. The B:C ratio compares the economic benefits with project costs, and IRR represents the rate of return associated with the investment.

Kumar *et al.* evaluated biogas plants of different capacities in Chhattisgarh and reported investment recovery periods of

approximately 3–8 years. The 3 m³ plant showed the highest B:C ratio among the evaluated capacities, indicating that plant size can influence economic performance [14].

Bedana *et al.* reported positive economic indicators for biogas plants in Bangladesh. With subsidy, the study reported an average NPV of USD 1629.11, B:C ratio of 1.77, payback period of 2.93 years and IRR of 48%; without subsidy, the corresponding average NPV, payback period and IRR were lower [15]. These results demonstrate the influence of financial support and operating conditions on the economic attractiveness of biogas technology.

Economic feasibility therefore depends on the combined value of energy substitution, digestate utilization and waste management, together with capital and recurring costs. Flexible plants may be economically attractive where installation requirements are low, feedstock is readily available and the generated biogas and digestate are effectively utilized. However, service life, membrane replacement and maintenance costs should be incorporated when comparing flexible systems with conventional digesters [4,13].

9. Environmental Benefits

Flexible biogas plants provide environmental benefits by converting biodegradable organic wastes into useful energy and digestate. Anaerobic digestion provides a controlled pathway for waste treatment while recovering energy as biogas and nutrients through digestate, thereby linking renewable-energy generation with resource recovery [1,17].

9.1 Organic Waste Management and Greenhouse Gas Reduction

Organic wastes from livestock, households, markets and food-related activities can create environmental problems when improperly stored or disposed of. Anaerobic digestion provides controlled treatment of these wastes while producing biogas and digestate. Flexible plants can support decentralized waste treatment because they can be installed close to the location where organic feed stocks are generated [4].

Capturing biogas also provides an opportunity to reduce uncontrolled methane emissions from decomposing organic matter. When the produced methane is collected and utilized as an energy source, part of the environmental burden associated with uncontrolled waste decomposition can be avoided [1]. However, the overall greenhouse-gas benefit depends on effective gas capture, leakage control, energy substitution and appropriate digestate management.

9.2 Reduction in Conventional Fuel Use

Biogas can substitute for LPG, fuelwood and other cooking fuels, thereby reducing demand for conventional energy sources. The environmental benefit depends on the quantity of biogas actually utilized and the type of fuel displaced [1]. In rural applications, reduced dependence on fuelwood may also decrease pressure on local forest resources.

9.3 Digestate and Nutrient Recycling

Anaerobic digestion converts part of the organic matter into biogas while retaining many nutrients in the digestate. Appropriate application of digestate can return nitrogen, phosphorus, potassium and organic matter to agricultural soils and may reduce dependence on purchased fertilizers [16,17].

The environmental value of digestate depends on proper handling and agricultural application. Application rate and management practices influence nutrient-use efficiency and

potential nutrient losses. Studies of bioslurry from flexible and fixed-dome systems have demonstrated its potential for agricultural use, supporting the role of digestate in nutrient recovery ^[16].

Overall, the environmental value of flexible biogas technology arises from the combined benefits of organic-waste treatment, methane recovery, energy substitution and nutrient recycling. These benefits are maximized when biogas is effectively captured and utilized, leakage is minimized and digestate is appropriately managed ^[1,16].

10. Challenges

Despite their advantages, flexible biogas plants face technical, environmental and operational challenges that can affect reliability, service life and user acceptance. The major concerns include membrane durability, leakage, temperature sensitivity, gas-pressure management, feedstock availability and limited technical support ^[3,4].

10.1 Membrane Durability and Leakage

The flexible membrane is one of the most critical components of a flexible biogas plant and is susceptible to degradation from sunlight, temperature variation, mechanical stress and accidental damage. Jamal *et al.* reported shorter operational lifetimes for balloon-type systems compared with fixed-dome and floating systems, highlighting durability as an important limitation ^[3].

Gas leakage may occur through damaged membrane sections, joints, valves or pipeline connections. Leakage reduces the quantity of gas available for useful applications and can compromise overall system performance. Improved membrane materials, protected installation, reliable joints and periodic inspection are therefore required to improve long-term reliability ^[4].

10.2 Temperature and Gas-Pressure Management

Flexible digesters may experience greater exposure to ambient temperature fluctuations than underground masonry systems. Low temperatures can reduce microbial activity and methane production, making seasonal performance particularly important in colder regions ^[5]. Underground installation, insulation and other low-cost temperature-management approaches can help reduce these effects.

Gas pressure is another practical limitation because sufficient and relatively stable pressure is required for reliable gas utilization. Flexible gas holders can experience pressure variation with changes in stored gas volume. External loading and suitable pressure-control arrangements can improve gas delivery while preventing excessive pressure ^[4].

10.3 Feedstock, Maintenance and Technical Support

Continuous operation requires a regular supply of suitable feedstock and water. Variations in feedstock availability and composition can therefore affect plant loading and gas production. Feedstock shortages may be particularly important for household systems that depend on daily waste or manure availability ^[1].

Although flexible plants generally require less structural maintenance than conventional systems, leakage repair, component replacement, cleaning and appropriate feeding remain necessary. Lack of technical support and inadequate user knowledge can contribute to poor operation or plant failure ^[1]. User training in feeding practices, basic troubleshooting, gas-line maintenance and digestate handling is therefore important for sustained operation.

The major challenge for flexible biogas development is therefore not only increasing gas production but also improving the reliability, durability and service life of the complete system.

Improved polymeric materials, standardized components, appropriate protection, simple monitoring and local technical support are important for reducing failures and increasing user confidence ^[3,4].

11. Recent Developments

Recent developments in flexible biogas technology have focused on simplifying installation, improving system integration, increasing durability and maintaining stable operation. The technology has progressed from simple flexible-bag and tubular digesters towards more standardized and prefabricated systems incorporating digestion, gas storage and gas-delivery components. Commercial systems such as Home Biogas illustrate the transition from simple flexible bags towards integrated household-scale systems ^[6].

Improved attention has also been given to digester design and operating conditions, including solids concentration, organic loading rate, temperature, pH, digester volume and gas-storage capacity. Appropriate control of these parameters can improve process stability and gas production ^[4]. Temperature-management approaches such as protected or underground installation and insulation are particularly relevant for flexible systems operating under variable climatic conditions ^[4,5].

The development of flexible systems is therefore increasingly directed towards integrated design, improved material protection, better gas-pressure management and simplified operation. These developments provide a basis for improving the reliability and applicability of flexible digesters in decentralized applications.

Further development should focus on combining improved flexible materials with simple monitoring and control approaches to increase service life, operational reliability and user acceptance.

12. Research Gaps

Although flexible biogas plants have demonstrated potential for decentralized waste treatment and renewable-energy production, important research gaps remain. Existing studies are distributed among plant design, feedstock utilization, performance and economic assessment, while long-term integrated evaluations under field conditions remain limited ^[3,4].

12.1 Long-Term Durability and Seasonal Performance

Long-term information on the mechanical and environmental durability of flexible membranes remains limited. Differences in material quality, climatic exposure and installation conditions make direct comparison between reported service lives difficult ^[3]. Multi-year field studies and standardized durability testing under different climatic conditions are therefore required.

Seasonal performance also requires greater attention because temperature directly influences microbial activity and gas production. Studies covering complete seasonal cycles would improve understanding of changes in biogas production, methane content and process stability in flexible systems ^[4,5].

12.2 Capacity and Standardized Performance Evaluation

Comparative studies of flexible plants with different capacities under similar feedstock and climatic conditions are limited. Household, institutional and community-scale

systems may differ in loading, gas storage, pressure and economic performance. Comparison is also complicated by differences in reporting methods. Studies may express gas production as total daily gas, gas per unit mass of feed or gas per unit mass of volatile solids. Standardized reporting of specific gas yield, methane content, VS reduction, OLR and HRT would improve comparison among flexible systems ^[4,7].

12.3 Economic and Digestate Assessment

Economic evaluations frequently use different assumptions regarding plant lifetime, fuel prices, subsidies, labour and digestate value, limiting direct comparison of reported economic results. Standardized life-cycle economic and sensitivity analyses are therefore needed ^[13,15].

Although digestate represents an important co-product, relatively limited long-term research has evaluated its effects on soil properties, nutrient availability and crop productivity specifically for flexible systems. Longer-duration field studies are required to establish its agricultural and economic value ^[16].

12.4 Digital Monitoring and System Optimization

Low-cost monitoring and control could improve the operation of flexible digesters, particularly where technical support is limited. However, practical validation of affordable monitoring systems under rural operating conditions remains an important research need. Future studies should therefore investigate simple approaches for monitoring parameters such as temperature, pH, gas production and pressure without substantially increasing system complexity or cost.

Table 5: Major research gaps and required research

Research gap	Required research
Membrane durability	Long-term field and accelerated-aging tests
Seasonal performance	Multi-season evaluation
Plant capacity	Comparative studies across capacities
Performance reporting	Standardized performance indicators
Economic assessment	Life-cycle and sensitivity analysis
Digestate utilization	Long-term soil and crop studies
Monitoring	Low-cost field-ready monitoring systems
Pressure management	Improved gas-storage and control systems

The major research need is therefore to move beyond short-duration gas-production experiments towards long-term, field-based and integrated evaluation of flexible biogas plants.

13. Future Perspectives

The future development of flexible biogas plants should focus on improving durability, reliability and adaptability while retaining the advantages of simple installation and decentralized operation. Improved polymeric materials and protective structures could extend membrane service life, while better gas-storage and pressure-control systems could improve the reliability of gas utilization ^[3,4].

Digital monitoring also provides an opportunity to improve operation by enabling measurement of temperature, pH, gas production and pressure. For rural applications, however, monitoring systems should remain low-cost, simple and robust rather than introducing unnecessary technical complexity.

Flexible digesters may also have potential for modular and community-scale applications, particularly where locally available organic wastes can be continuously supplied. Integration with other renewable-energy technologies and improved utilization of digestate could further increase the overall value of these systems.

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