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Review

Portable Biogas Digester: A Review

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Abstract: To reduce and convert biodegradable waste into energy-rich biogas, anaerobic digestion technology is usually employed. Hence, this takes place inside the biogas digester. Studies have revealed that these digesters are designed and constructed using bricks, cement, and metal; often require a large footprint; and are bulky and expensive. The innovation of portable biogas digesters has come into the market to address these challenges. This present review provides an overview of the in-depth and comprehensive information on portable biogas digesters in the literature. Areas covered in the review include the modification of the biogas digester design, the need for a portable biogas digester, recent studies on the factors affecting the performance of portable biogas digesters, and specific assumptions taken into consideration for designing any portable biogas digester. Convincingly, portable biogas digesters appeal to small rural families because of their ease of operation, maintenance, and ability to save space. The material for the construction and comparison of the portable biogas digester with other designs and the economic feasibility of the system were also reviewed. Implications: The full-scale design, fabrication, and utilization of a portable biogas digester are viable but not widely employed compared to other designs. However, there is a lack of readily available information on the portable design of biogas digesters. This review presents various aspects relating to portable biogas digesters and the quality of biogas produced. Therefore, the review suits audiences in energy process design and engineers, energy researchers, academics, and economists.

Keywords: anaerobic digestion; biogas energy; economic feasibility; plastics; renewable energy

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1. Introduction

Waste management is one of society's most significant issues, particularly in developing nations. Due to their detrimental environmental effects, waste management and reduction have risen to the top of the priority lists in several countries. They play a significant role in the shared duties and efforts to lower pollution and greenhouse gas emissions, the primary causes of global climate change. The old method of disposing of the waste is no longer acceptable due to its unfavorable effects [1]. Therefore, it is imperative to look for sustainable energy sources that are renewable and beneficial to the environment. Biogas provides such sustainable renewable energy. By substituting renewable energy sources like biogas for fossil fuels, the carbon cycle is closed, and it lowers the atmospheric concentration of carbon dioxide and the quantity of pollutants in the atmosphere. It is observed that the use of biogas has the potential to reduce both NOx and smoke emissions simultaneously via high charge compression ignition (HCCI). This offers ultra-low emissions with better performance, as experimentally reported by Feroskhan et al. [2]. The use of HCCI was effective in the study in diminishing the pollutants in the exhaust. This might be attributed to the valve overlap and the adjusted injection timing. Also, by increasing the biogas energy ratio, the HCCI mode was said to be more effective in reducing NOx than the standard compression ignition (CL) operation, even though the hydrocarbons (HCs), carbon monoxide, and smoke emissions were higher.

Methane, carbon dioxide, and trace amounts of hydrogen sulfide, ammonia, nitrogen, and hydrogen make up biogas, with methane as the major combustible gas of biogas.

Waste materials such as cotton, agricultural and municipal trash, and industrial and animal waste are often used as feedstock for biogas production. In addition to the previous feedstock mentioned, biomass, such as cattle dung, crop wastes from agriculture, and chicken droppings, has the potential to be converted into biogas by regulated anaerobic degradation [3]. Biogas can be used directly to produce heat and electricity as a by-product of microbial metabolism or processed to produce biomethane and value-added compounds for use in energy and industrial processes [3]. The gas has excellent potential for utilization as a renewable resource, and its use can help reduce greenhouse gas emissions. For instance, in 2014, biogas accounted for 0.29% of Switzerland's total energy consumption and over 8% of all renewable energy production, excluding hydropower in the country. Using biogas as cooking fuel can help lessen reliance on solid biomass sources like firewood [3]. By 2040, biogas will have the potential to supply cooking fuel to approximately 200 million people, mainly in Asia and Africa. This suggests that biogas plays a big part in making the social development goals (SDGs) a reality. Upgraded biogas yields more biomethane than raw biogas, making it a better fuel. The transition to a green, low-carbon energy and electricity mix presents biogas as a dependable energy resource [4]. The process of biogas production is from anaerobic digestion technology. In anaerobic digestion (AD), the organic materials of any substrate are broken down by bacteria through a series of biochemical events into a gaseous mixture (CH_4, CO_2, H_2, H_2S, etc.) without free oxygen. The increase in anaerobic digestion for treating industrial and municipal waste has caused a slowdown in rural energy conservation since the latter part of the 1980s. In the anaerobic digestion process, oxygen usually prevents some types of bacteria from surviving, resulting in an anaerobic (oxygen-free) environment.

According to Uddin and Wright [5], the anaerobic digestion process occurs in a closed tank or vessel known as a biogas digester. Also, it can be defined as any structure that helps and facilitates organic materials to break down and produce biogas. The size and form of a biodigester might vary based on the users' needs and the materials' availability [6]. Notably, the poor design of the biogas digester results in low biogas yield, the bulkiness of the digester, and the accumulation of toxic gasses [7]. However, various factors have been reported to be responsible for biogas digester failure after construction and installation, especially in low-income countries. For instance, in sub-Saharan Africa and Sri Lanka, the application of biogas digesters lacks long-term sustainability, and soil conditions, vibration patterns, and the correct positioning of the digesters are not considered during construction. This has resulted in cracking and leaks [8]. The lack of user training operation and maintenance issues, as well as a poor understanding of basic troubleshooting, is a problem in terms of sub-optimal feeding practices. Also, difficulties have occurred in the digester function because of solid digestate incrustation floating in the main tank. This tends to reduce biogas production [9]. The mixing ratio is another problem biogas digesters usually encounter after installation and construction. Finding the correct ratio of animal manure to water (slurry) due to a lack of knowledge or the unavailability of water, according to Puzzola et al. [10], has caused processing problems. In Zimbabwe, a large-scale clean energy project designed to demonstrate the sophisticated nature of biogas systems collapsed because of a lack of availability of spare parts. This is based on the mechanical failures responsible for the poor functionality of the system. This has led to the inability to quickly and cost-effectively source and fit spare parts, which is a major implication for biogas digesters in the rural setting [11]. Mwirigi et al. [8] mentioned that an absence of trained technicians in the locality of biogas digester is a factor and exacerbates issues in low-income African countries.

Despite the challenges and limitations of the biogas digester systems after installation and construction, there have been efforts to modify these systems to enable the desired biogas yield through portable biogas digesters. This present study reviewed recent advancements in the literature regarding the various concepts and aspects of portable biogas digesters, such as designing and construction, application, economic feasibility, etc., to benefit small-scale households and enhance waste management; thereby converting domestic waste into valuable alternative sources of energy. Therefore, the portability factor makes the biogas digester attractive and attracts global attention from rural inhabitants, thereby addressing porosity issues that might prevent it from being gas-tight.

2. Modification of Biogas Digester Designs

Fixed-dome, floating drums, and balloon biogas digesters have been modified into portable biogas digesters. This section presents a brief discussion of those designs.

Fixed-dome digester: A fixed-dome digester is a closed, dome-shaped structure with an immovable gas holder and a displacement pit used in biogas plants (See Figure 1). It consists of a digester with a fixed gas holder that sits on top, storing gas in the upper part of the digester [12]. Prior to the biogas production, the slurry is moved into the compensation tank or digester chamber. The amount of gas stored and the height differential between the slurry levels in the digester and the compensation tank cause the gas pressure to rise. A fixed-dome biogas digester is known to be cheap, has no moving part, and is simple to operate and maintain. During the design of the fixed-dome biogas digester, there were no rusting steel pieces, which provided an anticipated long plant life of 20 years or more. Usually, the fixed-dome biogas digester is designed underground. Hence, the digester is shielded from physical harm and conserves space [13]. Sunlight and warm seasons take longer to heat the subterranean digester than during the day, and it is sheltered from low temperatures at night and in the winter. The digester's temperature does not fluctuate during the day or night in a way that benefits bacteriological activities. The design of a fixed-dome biogas digester offers and creates local job opportunities because of the extensive labor required. Hence, building the fixed-dome digester can be a challenging task. Therefore, professional skills and knowledge are required during construction to avoid cracks and porosity and make it gas-tight [14]. Figure 1 shows the schematic diagram of a fixed-dome biogas digester.

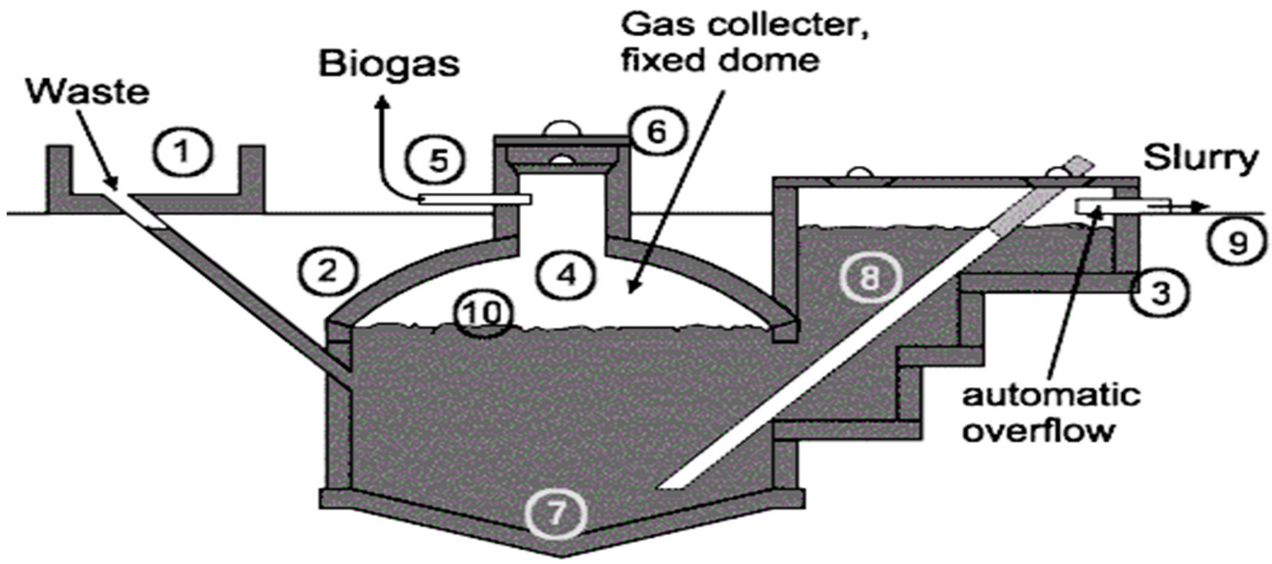

Figure 1. Fixed-dome biogas digester [15].

Floating drum digester: The floating drum biogas digester is an efficient system for decentralized blackwater treatment in various settings. This type of biogas plant is highly recommended due to its universal applicability, easy maintenance, and versatility for domestic, community, institutional, industrial, and commercial applications. The design typically includes a reception tank for organic matter, a digester where anaerobic digestion occurs, a gasholder for collecting gasses like methane and carbon dioxide, and an overflow tank for discharging processed sludge. The gas produced in the digester in the first few weeks is mainly carbon dioxide, which is not flammable and can be released into the atmosphere. Based on this, the flammable methane content of the gas starts increasing and can be used as fuel when it reaches over 45% methane volume [16]. The floating drum biogas digesters have been widely introduced, especially in rural areas in India, where it is known as Gobar gas plants. "Gobar gas" refers to biogas produced specifically from cow dung. The floating drum biogas digester has proven to be environmentally friendly, providing benefits such as soil nutrient enrichment and an alternative energy source. Moreover, the floating drum biogas digester offers a sustainable solution for managing human and animal wastes, converting them into valuable resources like biogas and nutrient-rich sludge. Despite minor concerns such as potential leaks contaminating water supplies or emissions like hydrogen sulfide causing eye irritation, proper management and maintenance can mitigate these issues effectively. Overall, the floating drum biogas digester represents a practical and environmentally sound method for treating waste, producing biogas for energy needs, and generating nutrient-rich by-products for agricultural use, showcasing its potential for decentralized waste treatment in diverse locations [17]. Figure 2 shows the schematic diagram of a floating drum biogas digester.

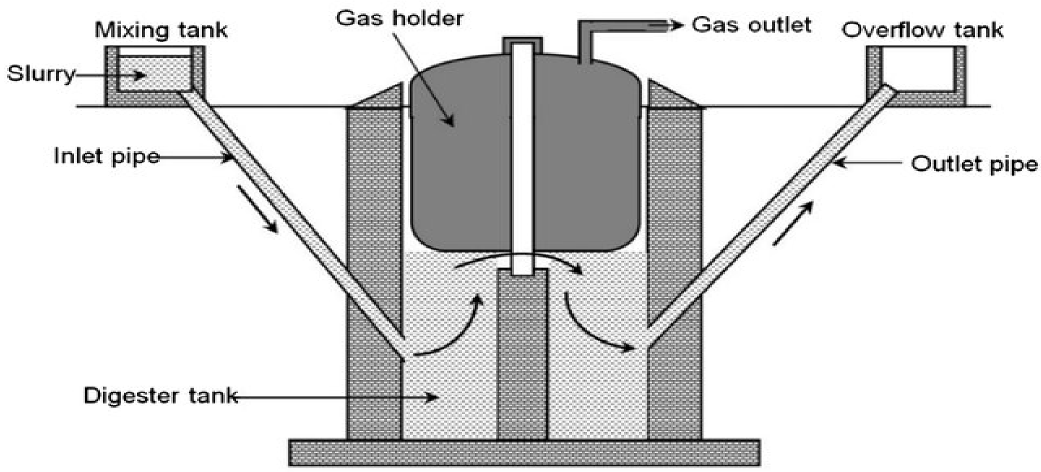

Figure 2. Floating drum biogas digester [14].

Balloon digester: Balloon biogas digester refers to a type of renewable energy generator that utilizes heat-sealed plastic or rubber bags to convert organic waste into gas for cooking power [18]. One key advantage of the balloon digester is its standardized prefabrication at low cost, making it an economically viable option for biogas production. Its ease of transportation and shallow installation make it suitable for areas with high groundwater tables and warm climates requiring high-temperature digesters [19]. However, the portable balloon digester does have limitations. Its relatively short useful life span of 2–5 years and susceptibility to mechanical damage pose challenges, especially in areas with limited local repair expertise. There is a need for safety valves to prevent damage from exceeding gas pressure, and there is a need for gas pumps if higher pressures are necessary to add complexity to their operation. Moreover, the plastic balloon's vulnerability to damage and scum removal issues during operation further highlights some of the drawbacks of this digester design [20]. Despite its disadvantages, the balloon digester offers a practical solution for biogas production in specific contexts. Its uncomplicated cleaning, emptying, and maintenance processes and the ability to utilize difficult substrates like water hyacinths make it a viable option where cost advantages are substantial and local repair capabilities exist or can be established. The balloon digester's simplicity, low construction sophistication, and suitability for specific environmental conditions make it a valuable choice for biogas production in areas where its limitations can be effectively managed [21]. Figure 3 shows the schematic diagram of the balloon biogas digester.

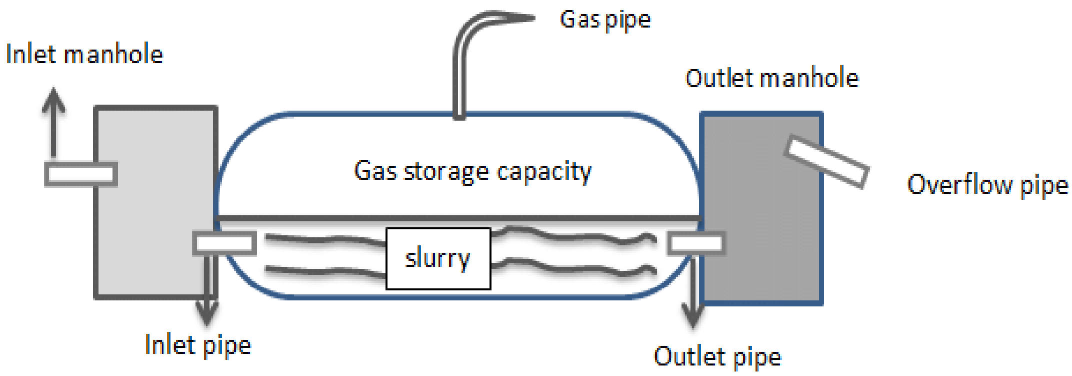

Figure 3. Balloon biogas digester [22].

Having looked at the description of various biogas digesters in Section 2, it is necessary to briefly review the factors affecting anaerobic digestion performance, which is also applicable to portable digesters. This is achieved from recent publications or studies.

3. Recent Studies on Factors Affecting the Performance of Portable Biogas Digesters

3.1. Temperature

The performance of anaerobic digestion is said to be affected by temperature, thereby influencing the metabolism of the microbial community. Hence, this gives rise to anaerobic digestion processes and improves stability and efficiency [23]. According to the literature, biogas production is optimal under mesophilic (32 to 45 °C) and thermophilic (55 to 70 °C) temperature conditions. At the mesophilic temperature, the anaerobic bacteria break down organic matter and produce methane thrive. However, maintaining the same temperature in the biogas digester is crucial and required. Methanogens and thermophilic methanogens are temperature-sensitive, which is why this is carried out. Most notably, compared to mesophiles, thermophilic methanogens are less diverse. Under typical circumstances, there should be no more than a ±3 °C variation [24]. However, the energy expenditure for these types of temperatures makes it undesirable for low-cost smallholder digesters, which are frequently associated with ambient temperatures. The efficiency of unheated smallholder digesters varies with the seasons, producing less biogas in the winter. Low temperatures cause AD to fall into the psychrophilic (20 °C) range, thereby affecting the reaction rate and time needed to complete the degradation process. Psychrophilic anaerobic digestion (PAD), whilst unstable, requires no additional energy to heat digesters and can be used as a reliable, energy-efficient technology capable of substituting mesophilic and thermophilic anaerobic digestion, especially in cold regions, if optimized [25]. Therefore, temperature is a critical factor affecting portable biogas digesters' performance and efficiency.

Portable biogas digesters are often designed to maintain this temperature range to ensure consistent and efficient biogas generation [26]. However, temperature fluctuations can disrupt the delicate balance of the anaerobic digestion process. If the temperature drops below the optimal range, the bacteria become less active, slowing biogas production. Conversely, if the temperature rises too high, it can kill the bacteria and completely break down digestion. The portable biogas digesters often incorporate temperature monitoring and control systems (substrate heating technique—In-vessel method) to maintain the optimal temperature and minimize the impact of external temperature changes [27]. The In-vessel heating system is recommended because of its homogeneous heat transfer and uniform substrate heating distribution throughout the slurry volume without a stirrer. However, heating the substrate to its optimum is not enough; temperature control automation is needed to maintain a constant temperature. Temperature control automation helps quickly restore the substrate's temperature when it goes below or above the optimum, as reported by Makamure et al. [28]. Furthermore, to address the temperature sensitivity of portable biogas digesters, some models are equipped with optional temperature probes that can be inserted directly into the gas stream to measure the temperature accurately. These data can be used to monitor the digestion process and make necessary adjustments to maintain the optimal temperature range, ensuring consistent and efficient biogas production [29].

3.2. pH

Methane cannot be produced if the pH value is higher than 8.5 or lower than 6.0. When there is a significant buildup of volatile fatty acids, pH decreases, and when there is a significant buildup of ammonia, pH rises. Digesters also include two typical buffering substances that maintain the pH inside. Carbonate bicarbonate buffering substance typically occurs and adjusts for shallow pH values. The ammonium buffering framework can provide a pH equilibrium of approximately 10. However, an excessively high organic loading rate (OLR), a drop in temperature, or the use of highly degradable feedstocks could overload these buffering systems [30]. The pH level plays a crucial role in the efficiency and functionality of anaerobic digestion processes within biogas digesters. Maintaining an optimal pH range is essential for the microbial activity responsible for biogas production. Research indicates that pH is a significant factor in the stability and performance of anaerobic digestion systems. A study focusing on biogas production from the co-digestion of untreated primary sludge highlights the importance of pH in sustaining functional anaerobic conditions for adequate digestion. This underscores the necessity of monitoring and controlling pH levels to ensure the proper functioning of biogas digesters [31]. The feedstock composition and the carbon/nitrogen ratio are key factors influencing biogas production, with pH being a critical parameter impacting the overall process. Proper pH levels are essential for maintaining the microbial community's activity and ensuring the breakdown of organic matter into biogas. Variations in pH can disrupt the microbial balance, leading to reduced biogas output and process inefficiencies. Therefore, understanding and managing pH levels is vital for optimizing biogas production efficiency [32]. Moreover, the pH of the fermentation medium directly affects the microbial activity responsible for biogas generation. Studies have shown that an optimal pH range is necessary to support the growth and function of methanogenic bacteria, which are crucial for methane production in anaerobic digestion processes. Deviations from the ideal pH range can inhibit microbial activity, decreasing biogas yields. Hence, maintaining the appropriate pH levels is essential for maximizing biogas production and ensuring the stability of biogas digesters [33]. In summary, pH is a fundamental factor that significantly influences the performance and efficiency of biogas digesters. Research emphasizes the critical role of pH in sustaining anaerobic conditions, supporting microbial activity, and optimizing biogas production from various feedstocks. By carefully monitoring and controlling pH levels within biogas digesters, operators can enhance biogas yields, improve process stability, and maximize the energy recovery potential of anaerobic digestion systems [34].

3.3. Hydraulic Retention Time

Hydraulic retention time (HRT) plays a crucial role in the efficiency and performance of portable biogas digesters. A shorter HRT can be advantageous in portable digesters as it allows for the quicker processing of organic materials, leading to faster biogas production. Research has shown that reducing the HRT in anaerobic digestion systems can increase methane production significantly without deteriorating system performance, as observed in the studies where methane production doubled when the HRT was decreased. Notable, HRT varies with temperature; an increase in temperature reduces the HRT of the substrate in the anaerobic digester. Krishania et al. [35] stated that in tropical areas such as India, the HRT varies from 30 to 50 days and is dependent on the weather conditions. This highlights the importance of optimizing HRT in portable biogas digesters to enhance biogas yield while maintaining system efficiency [5]. Moreover, the impact of HRT on the solubilization extent in anaerobic digestion systems is noteworthy. Studies have demonstrated that a decreased HRT, resulting in higher organic loading rates, can lead to a greater solubilization extent in digesters, ultimately improving the conversion of organic materials into methane. This finding underscores the significance of HRT management in portable biogas digesters to maximize feedstock conversion efficiency into biogas, making them more effective and productive for energy generation [36]. Furthermore, the operational flexibility offered by adjusting HRT in staged anaerobic digesters can influence the microbial ecology within the system. By altering HRT, it becomes possible to study the impact of this parameter on the microbial community composition, which is crucial for the overall efficiency of the digestion process. This adaptability in HRT management allows for a deeper understanding of how microbial communities respond to changes in operational parameters, aiding in optimizing portable biogas digesters for enhanced performance [37]. In conclusion, managing hydraulic retention time is critical in designing and operating portable biogas digesters. By carefully adjusting HRT, it is possible to improve biogas production, enhance solubilization efficiency, and influence the microbial community composition within the digesters. These findings underscore the importance of optimizing HRT as a critical parameter in the operation of portable biogas digesters to ensure maximum efficiency and productivity in biogas generation processes [38].

3.4. Carbon/Nitrogen (C/N) Ratio

The C/N ratio is a crucial factor affecting portable biogas digesters' performance. A C/N ratio of 20 to 30 is optimal for anaerobic digestion. If the C/N ratio is too high, methanogens will consume nitrogen rapidly, resulting in low gas production. Conversely, if the C/N ratio is too low, nitrogen will be liberated and accumulated as ammonia, increasing the pH in the digester [39]. According to Induchoodan et al. [40], the production of biogas is significantly reduced due to ammonia accumulation since they are toxic to methanogens. Based on this, one method to avoid the excessive production of ammonia during anaerobic digestion is to increase the C/N ratio of the feedstock. This can be performed by co-digesting other waste feedstocks high in biodegradable carbon to enhance the performance of the anaerobic digestion process. Also, it helps to optimize the C/N ratio to maintain the proper ratio balance, which is necessary for optimizing biogas production. The benefits of increasing the C/N ratio to an optimum level through co-digestion result in higher biogas yield and a reduction in potentially toxic ammonia concentration [41]. Food waste mixture at a C/N ratio of 17 was combined with meat, fruit, and vegetable wastes to increase its C/N ratio to 26 and 30. The result of the study showed that biogas yield obtained during digestion increased to 0.352 L/gVS, 0.447 L/gVS, and finally to a maximum yield of 0.679 L/gVS at the C/N ratios of 17, 26, and 30, respectively. This is attributed to the digestion medium's enhanced buffering effect [41]. The co-digestion of potato waste (a C/N ratio of 35) and beet leaf (a C/N ratio of 14) increased the biogas yield by 60% compared with the digestion of potato waste alone, as evaluated in Khanal et al.'s [42] study. Another study found that dairy manure, chicken manure, and wheat straw co-digestion performed better in methane potential than individual digestion. As the C/N ratio increased, methane potential initially increased and then declined, with the C/N ratios of 25:1 and 30:1 showing better digestion performance with stable pH and low concentrations of total ammonium nitrogen [43]. The impact of C/N ratios and organic loading rates (OLRs) on the anaerobic digestion of paper, cardboard, and tissue wastes with food waste was conducted. The experiment was carried out in batch digesters with co-substrates having C/N ratios of 25 and OLRs of 15 gVS/L. The results showed that the C/N ratio is a crucial constraint in anaerobic digestion [44]. A study on biogas production from carica solid waste found that the optimum biogas production was obtained at a C/N ratio of 25 compared to a C/N ratio of 30. The kinetic constant of biogas production had the highest production rate (Rm) of 1.7825 mL/g TS/day with a total solid (TS) content of 9% and a C/N ratio of 25 [45]. It is interesting to note that the volatile solid (VS) destruction is an indication of the percentage of solid and organic pollutant removal from waste (substrate) during anaerobic digestion. The volatile solid concentration of any substrate provides useful information about the biogas yield and the digester efficiency. A study was conducted to examine the VS removal of different substrate compositions co-digested and the corresponding quantities of biogas yield. It was revealed that the cumulative biogas yield from these substrates increases with increasing VS removal as follows: 23.60%VS (1.01 kg), 60.75%VS (2.01 kg), 84.72%VS (2.55 kg), and 91.10%VS (2.88 kg) [46]. This indicates that the volatile solids contribute to the behaviors of the microbial activities involved in the digestion of a substrate.

3.5. Organic Loading Rate

The organic loading rate (OLR) plays a significant role in the performance of portable biogas digesters. Studies have shown that OLR is a crucial factor affecting anaerobic digestion for biogas production, influencing the stability and efficiency of the process. Higher OLRs can enhance the processing efficiency of anaerobic digestion but may also inhibit biogas production, highlighting the delicate balance required for optimal performance. The maximum achievable OLR was 9.00 g VS/(L·d), with varying volumetric biogas yields for mesophilic and thermophilic systems [47]. Research has indicated that the impact of OLR on biogas yield is significant, with studies focusing on various substrates such as food waste, water hyacinth, and cow dung. The findings suggest that increased OLR can lead to higher methane yields, with up to 89% of methane produced from cow dung under specific OLR conditions. However, exceeding optimal OLR levels can accumulate volatile fatty acids (VFAs) due to overloading, potentially hindering digestion [48]. Moreover, the variation in biogas yield at different OLRs underscores the importance of carefully managing organic loading in anaerobic digestion systems. Studies have demonstrated that different OLR levels can impact the daily biogas and methane production rates, with higher OLRs potentially prolonging the lag phase of biogas production due to increased organic matter availability within the reactor. Understanding the effects of OLR on digester performance is crucial for achieving stable operation and maximizing biogas production efficiency in portable biogas digesters [49].

4. Why Portable Biogas Digester

Generally, biogas digesters have the potential to deliver biogas at a higher efficiency because of better infrastructure, control of heating, and other operating parameters. However, the installation cost is high, which requires the government's intervention for subsidies [50]. According to Yalcinkaya et al. [51], the diversity of organic wastes, transportation, and maintenance costs contributes to the increase in the profitability and feasibility of biogas digesters. Portable bio-digesters are designed to be smaller and more compact compared to large-scale industrial bio-digesters, making them suitable for household applications (cooking, heating, and electricity generation). These biogas digesters are engineered to be compact, lightweight, and easy to install in small spaces like backyards, balconies, or terraces. They typically have a 0.5–2.5 m^3 capacity, as shown in Figure 4.

Figure 4. Portable biogas digester [52].

The portable type of biogas digester is user-friendly, with few moving parts and simple controls, requiring minimal maintenance [53]. For the sake of the application of a portable biogas digester in research, it deals with mostly the convenience of easy transportation, among other benefits. Moreover, like other large biogas digesters, the portable biogas digester also usually produces methane gas. To have a biogas digester at home (especially in densely populated areas and under difficult conditions), the possible and easy option is to have a portable biogas digester. Portable biogas digesters are guaranteed to be installed at any place with the help of minimum financial resources to reduce waste and provide valuable energy [54]. Recently, anaerobic digesters have faced certain limitations regarding the application, high cost of operation, and mostly large areas of space. One way to address this is through designing and installing portable biogas digesters, which are utilized for cooking and lighting operations in rural residential areas [23]. By so doing, it offers easier operation and reduces as well as eliminates the cost of land and material required for construction/installation.

Since the fixed-dome and floating drum models are usually designed and constructed underground, they are immobile. On the other hand, the portable biogas digester provides mobility and is low-cost [55], which is advantageous. Mushtaq et al. [56] stated that portable biogas digesters tend to have a long life and have the capacity to generate biogas sufficiently. This was revealed after the test running of the designed floating dome-type portable biogas digester, which was found to help farmers in remote areas of Pakistan. To conclude, it is necessary to provide the different types of portable biogas digesters as presented in Table 1.

Table 1. Different types of portable biogas digesters and their properties and specifications.

Types of Portable Digester	Volume of the Digester (m^3)	Material Used for Fabrication	Biogas Generation (m^3)	Advantages	Disadvantages	Organic Loading Rate (kg/L)	References
EZ digester	1.5	Modified plastic	-	Provides mobility, compactness, and low cost with rich energy content	Provides inefficient agitation and inability to control the temperature	0.03	[23]
Africa green energy technologies(AGET digester)	2.5	-	2 m^3 biogas per day	Provide easy transportation	Provides inefficient mixing and is expensive	-	[23]
Plug flow-type digester	2.5–7.5	Plastic	-	Provides effortless handling and transportation, operates in rigorous climatic conditions, and has low construction and maintenance costs.	The absence of a stirring mechanism, low conversion rate of solids, and the necessity of periodic cleaning	180	[55]
Self-pressurized portable biodigester	0.05	High-density polyethylene (HDPE) plastic	0.04 m^3 biogas generated within 35 days HRT			0.032	[57]

5. Design and Assumption Consideration for Portable Biogas Digesters

The dimensions of the biogas digester and the construction materials are important factors of consideration during the design and fabrication stage [58]. The same applies to portable biogas digesters as they contribute towards obtaining methane yield and good quality biogas. However, Alkhalidi et al. [59] stated that the size of the digester and the biogas yield are the main parameters controlling the design of portable digesters. Table 2 further compares the design of a portable biogas digester with other designs.

Table 2. Comparison of portable biogas digesters with other designs of biogas digesters.

Portable Biogas Digester Designs	References	Other Designs	References
Easily transportable and adaptable to various settings.	[26]	They consist of a dome-shaped, fixed gas holder made of bricks or concrete.	[58]
They are made of prefabricated modules that can be quickly assembled and disassembled.	[19]	No moving parts needed.	[60]
Versatility to be customized for different organic waste sources and biogas output needs.	[6]	A long lifespan of 20+ years if well built.	[61]
Relatively low cost compared to other digesters due to less infrastructure and use of low-cost material.	[62]	They have high costs because they require human labor to build and have relatively high-cost materials.	[63]
A volume of 0.2–3.6 m^3 even up to 7.5 $m^{3.}$	[55,64]	The digester volume is fixed, so it cannot be expanded later.	[65]
Ability to generate biogas from food, agricultural, livestock manure, etc.	[66]	Require skill for construction.	[67]

From the literature, fixed-domes, floating drums, and balloon biogas digesters have been modified in one way or the other into portable digesters because of their benefits. However, in terms of design and construction, the floating drum and fixed-dome biogas digester usually use a fixed mild steel drum (usually placed on the top of the digester) and brick masonry in cement mortar (fixed digester chamber), respectively, for the purpose of collecting gas produced from the digester. Hence, for portability's sake, the design consideration has been made, thereby employing and modifying the fixed mild steel and brick masonry in cement mortar used in floating drums and fixed-dome digesters, respectively, to use moveable steel vessels [1]. Similarly, studies by Osueke et al. [68], Leyva et al. [69], and Yinquan and Yinhu [70] emphasized the need for Styrofoam, polyethylene sheet, fiberglass-reinforced plastic, and other available durable and easy-to-fabricate materials for the same application. Looking at the balloon biogas digester consisting mostly of PVC at the upper part for gas storage, the gas pressure is achieved by placing weights on the balloon. To improve this through modification, a bike pump was used in the portable digester design to increase and boost the pressure and velocity to suit the modern-day gas cooker design [1]. Specific restrictions are made for portable biogas digesters with respect to other designs. For instance, in terms of pressure, pressure vessels are categorized as thin shells or thin-walled and thick-walled. If the ratio of the inner radius to the wall thickness of the pressure vessel is greater than or equal to 10, then it is referred to as thin-walled; otherwise, they are defined as thick-walled [71]. The portable biogas digester is usually designed as a vertical thin-walled pressure vessel according to Nkoi et al.'s [1] study. For temperature control strategies, the portable biogas digester employed the utilization of a greenhouse with a double layer of polyethylene plastics and warm water heated by solar energy or a thermal insulation container, as noted in Mutungwazi et al. [22] and Rossel-Kipping et al. [72]. In the case of organic loading rate, the key factor deals with the agitation of the digester during the operation. The purpose of the agitation of the feedstock or substrate is to blend the fresh material with the digestate-containing microorganisms. It is interesting to mention that the type of agitation equipment rate and the amount of agitation depends on the digester type as well as the solid content in the digester, as pointed out by Mutungwazi et al. [22]. Preferably, an anchor impeller with a diameter of 95% of that of the vessel was designed and recommended because it is gentle and slow for the thick paste agitation of most substrate slurries according to Darwin et al. [73]. Moreover, incorrect or inefficient agitation equipment will result in longer retention time and decreased biogas production. Having looked at the selective technical issues based on design/construction, restrictions, and organic loading rate as it relates to portable biogas digesters, the authors sought it necessary to provide information on the energy and material design as presented in Table 3. No recent report has focused on this, making it a bit difficult to examine the proposed designs as it affects the policymaking on promoting biogas technology. Table 3 presents the general and common design factors and procedures for portable biogas digesters.

Table 3. Design procedure and factors for portable biogas digester.

Design Consideration/Procedure	Notes
The estimation of biogas requirement and waste feed rate	A total of 1 m^3 of biogas is required for cooking. The feeding rate depends on the type of feedstock. For design purposes, the lower value of 10% total solid is considered, this implies that 1 kg of waste results in 0.1 kg of TS present
The estimation of the mass of water	The pre-knowledge of the total solid in the feed is required to be known before the design of the portable digester [68]. The increase in total solids from 10% to 20% results in a reduction in methane production. Due to mass transfer limitation, the production of methane ceases when the total solids are 30%. Therefore, total solids of 7–9% are recommended to be maintained in the feed.
The estimation of hydraulic retention time	The hydraulic retention time is affected by the temperature and geographic location. For instance, hot regions are expected to have lesser hydraulic retention time (<30 days) as compared to tropical regions. On the contrary, in cold regions, the hydraulic retention time is usually above 50 days. The hydraulic retention time is important during the calculation of the size of the digester.
The estimation of the volume of the slurry and gas holder	Interestingly, the total slurry of the feedstock depends on the rate of feed and hydraulic retention time, whereas the volume gas holder is a function of gas generation and consumption.

As noted in Table 3, the issue of total solid is critical based on the utilization of organic matter in the raw material. The increase in the total solid content increases biogas production. However, for the optimum performance of the biogas digester for biogas production, the dry fermentation of organic waste is preferred and usually employed. Having looked briefly at the design procedures and factors for portable biogas digester, specific assumptions are made to fit into the procedures and factors, as stated in Alkahalidi et al. [59]. These assumptions include the following:

- Total mass is assumed as the mass of the solid waste plus the mass of the water (for instance, 20 L of water for 10 kg of dry waste)
- The ratio of the diameter (D) to the height (H) of the portable biogas digester is assumed to be D:2H.
- The slurry chamber height in the inlet and outlets depends on the maximum pressure attained by the gas, which is equal to the pressure of the water slurry above the lowest slurry level in the inlet and outlet tanks. Usually, for a safe limit, a pressure of 0.85 m water gauge is often used.
- In a scenario where the diameters of the inlet pipe were not available in the range of ±15 to 20 cm, the inlet and outlet tank were not in the same dimensions. Therefore, the inlet diameter is said to be slightly higher.

6. Material for the Construction of Portable Biogas Digesters

The material for designing, fabricating, and constructing anaerobic portable biogas digesters depends on the geological, hydrological, and local conditions and available materials. Different materials with improved properties and cost-effectiveness have been introduced into the market to design and fabricate portable biogas digesters. During the review, it was attained that plastic is the most common material for constructing portable biogas digesters, as shown in Table 4. This is attributed to the properties they possess.

Table 4. Properties of materials for portable biogas digester [19].

Materials	Advantages	Disadvantages
PVC	Less weight and easily portable as well as easy to install and of flexible design	Short life span and requires regular maintenance
PE	Cheaper compared to PVC	-
Neoprene rubber	Weather resistance	Expensive/low pressure/less life span
Steel drum	Leak proof and ability to produce gas at a constant flow	Corrosion and heavy weight of the gas holder
Fiber-reinforced plastic (FRP)	High strength to weight and durability; resistance to corrosion	High cost and limited fire resistance; potential debonding issue; may lose strength and stiffness at high temperature.
Waterproof adhesive	Strength and resilience to withstand moisture, humidity, and immersion	Difficult to remove once cured, decreases at high temperature, and susceptible to freezing at low temperature; lower water resistance than solvent-based products.
Heat-sealed plastic/rubber	Simple design and low construction.	Limited durability and may require frequent replacements.
Concrete	Durable and long-lasting.	Expensive and requires professional masonry

7. Previous Studies on Portable Biogas Digesters

Ajay et al. [74] studied decentralized energy from portable biogas digesters using kitchen waste. The review was motivated to address the scanty portable biogas digester gap in the literature, especially regarding small-scale designs. As a part of contributing to the study on portable biogas digesters, the authors reviewed the different kitchen waste management techniques and types of portable anaerobic biogas digesters and their design. The study findings revealed kitchen waste as a feedstock that has the potential to produce energy in an enclosed air-tight container known as a biogas digester. Also, a portable biogas digester is seen as a blooming attractive alternative to produce biogas domestically, especially at a small-scale level. This has been employed in the urban area. The review outlines the systematic design of biogas digester units and the proper feeding of kitchen waste. The authors concluded the study by recommending that the design of portable biogas digesters in the literature needs to be modified, thereby improving the technical factor that deals with the design of the biogas unit.

A portable biogas digester was designed and fabricated using a self-pressurized container. The study, which was carried out by Singh et al. [57], used three plastic containers of volumes 0.05 m^3, 0.05 m^3, and 0.035 m^3. These containers were designed as digesters, water storage tanks, and gas storage tanks, respectively. The study was conducted to mitigate the problem of managing food waste and the capability of portable biogas digesters to handle domestic kitchen waste. Carbon steel, which is usually used for spring manufacturing, was also used to maintain the gas pressure of the digester because of its mechanical properties. It was discovered that the pressure was developed inside the portable biogas digester, which resulted in the upward movement of gas. The produced gas in the biogas digester enters the gas holding unit through the hole provided. The study revealed that 0.04 m^3 of biogas was generated from the kitchen waste. Hence, the biogas produced contained 67% methane content as the major gas.

One of biogas's applications is its use in electrical generators, which have recently gained much interest. This was shown in Pacis et al.'s [50] study on the fabrication of a portable biogas digester capable of running a Stirling engine coupled with the alternator. In their study, the authors fabricated the biogas unit using plastic. In contrast, during construction, the outlet pipe of the biogas was connected to a Bunsen burner, which, in turn, was connected to the stirring engine. Similarly, Zeynali et al. [75] designed a portable biogas digester of volume 0.4 m^3. To ensure portability, one feature of portable biogas digesters, the entire assembly of the entire system (digester unit, the stirrer, and gas storage) was placed on a cart. Interestingly, the authors employed the circulating pump for efficient mixing.

Portable biogas digesters have been seen to be designed with additional features. This was confirmed in Kouya-Takala et al.'s [76] study. The authors designed a portable biogas digester with a suitable holding biogas storage unit. The design differs from the previous ones in that the entry of feedstock through the inlet pushes the digestate through the outlet. To maintain anaerobic conditions, the digester chamber is sealed hermetically. Considering the feeding mode, the digester was fed with cow dung and later introduced with kitchen waste because of the balance of nutrients. The portable biogas digester generated a cumulative biogas production of 1.994 m^3 after the 40-day retention time. In terms of the digestate, this was used as a fertilizer. In a similar study, additional features such as a pressure gauge, gas holding unit, and agitation (accessories) were constituted during the design and fabrication of a portable biogas digester. In the study by Nwankwo et al. [77], plastic was used to produce portable fermenters because it is corrosion-free. The digester fed with cow dung, cassava, and yam peels generated a cumulative biogas production of 16.829 m^3 and 0.601 m^3 of biogas per day during the 28th day of the monitoring period.

Nkoi et al. [1] modified the existing design of flexible balloon biogas digesters and floating drums to design and fabricate a portable type of biogas digester. Alterations were made in the study such that the digester chamber of the portable digester was designed using steel against the bricks commonly used for floating drum digesters. The reason for using the steel material was because of portability. Other materials used in the design include fire detectors, relief valves, pressure gauges, and ball valves with diameters of 0.076 and 12.7 mm. Interestingly, a modification was made as regards the gas pressure. The gas pressure design is essential during the design and fabrication of the biogas digester. In this case, the gas pressure is attained for the flexible balloon digester by placing weight on the balloon's skin against the bike pump used to attain the required pressure in the portable digester design. It is important to state that the bike pump was modified and utilized to boost the pressure of the methane gas. Based on the feeding, the portable biogas digester was fed with 17 kg of cow dung and 34 kg of water, thereby generating a cumulative biogas yield of 0.055 m^3 after 12 days and a total biogas production of 124.3 L for the 30 days retention time.

To overcome and address the problem of energy needs and inefficient waste management systems experienced in densely populated poor and rural areas, Alkhalidi et al. [59] designed and fabricated three small-scale portable biogas digesters, each with a volume of 0.54 m^3. The portable biogas digester was fed with food waste, human waste, and human and food waste co-digestion, thereby determining their gas production. Findings from the study showed that the small-scale portable biogas digester fed with human and food waste co-digestion had the best result. This digester generated 115% of the family cooking gas requirement, and it is said to be utilized globally and not only in Jordan, where the study was conducted.

Issahaku et al. [27] conducted a review to investigate small-scale biogas digester design and construction to address the failure associated with small-scale portable digesters after fabrication and installation. The study was motivated by the frequent failures of small-scale and household portable biogas digesters, which hinder clean cooking fuel, thereby affecting the achievement of sustainable development goals (SDG 7). Based on the nature of the study, its methodology involves using the Scopus database-indexed peer-reviewed journals from 2000 to 2022 publications. The findings from the review suggested that the key design considerations of the portable biogas digester deal with the safety of digester design-produced biogas quality and the use of effluent. However, even though there has been extensive literature on the design consideration of the system, the authors opined that the findings could act as a recommendation for promoting sustainable energy and waste management, which can be helpful to policymakers and researchers.

The non-portability of the fixed-dome and floating drum biogas digester has caused no possibility of the relocation of the digester. Based on that, Sebayuana et al. [78] developed a 500 L capacity portable biogas digester made of stainless steel. With the aid of stainless steel, tungsten inert gas welding technology was used for the manufacturing. The choice of stainless steel in the study is to ensure that the biogas digester is corrosion-free. Including a manual agitator in the study indicates that the biogas digester can be operated in batch and continuous modes, increasing the system's performance. The nature of the design and the material employed in the study prompts the easy maintenance of the portable biogas digester. The research showed that the batch system generated a biogas yield of 3320 L for a 52-day monitoring period. In contrast, the continuous digester reported a biogas yield of 51.7 L per day during the 30 days of the experiment. The authors concluded by emphasizing that portable biogas digesters can be operated in batch and continuous processes. Hence, using a stirrer helps resist corrosion and easy operation and maintenance.

African Green Energy Technologies designed and constructed a 2.0 m^3 portable anaerobic biodigester. The digester was introduced with 5–8 kg of waste generated in the kitchen. It was reported that 2 m^3 of biogas was generated from the system daily. An additional feature in the design was the 12 W photovoltaic module installed to power the gas pump for the purpose of generating large amounts of biogas. One advantage of the design is that it provides convenient transportation. However, the system has the drawback of high cost and ineffective blending [53].

Having looked at the previous studies on portable biogas digesters, these system-generated biogas yields. Table 5 summarizes the biogas yield from different portable biogas digesters, mostly plastic materials. Importantly, the biogas yield from portable anaerobic digesters can vary significantly depending on the type of digester, operating conditions, and feedstock.

Table 5. Biogas yields from different types of portable biogas digesters.

Types of Portable Biogas Digesters	Type of Wastes/Feedstock	Biogas Yield (m^3/kg TS)	References
Plastic digester	Cow dung Domestic waste	0.18 0.17	[55]
Plastic digester (AGET portable digester)	Kitchen waste	2.0	[53]
Plastic digester (Little green monster digester)	-	2.0	[60]
Metallic digester	Cow dung	0.005	[1]
Plastic digester	Cow dung	0.00157	[79]
Plastic biodigester	Kitchen waste	0.000175	[78]
Plastic biodigester	Kitchen waste	0.000115	[80]
Plastic digester (agitated)	Cow dung	0.036	[23]
Plastic biodigester (balloon)	Cow dung	12	[20]
Floating drum portable digester	Banana peel	0.13182	[81]
Fixed-dome portable digester	Kitchen	5	[82]

8. Economic Feasibility of the Port Biogas Digesters

Several recent studies have demonstrated the economic feasibility of portable biogas digesters. These small-scale, decentralized biogas units offer cost-effective solutions for generating renewable energy from organic waste, particularly in developing countries. A vital advantage of portable biogas digesters is affordability and accessibility to low-income households. Families of three or four can meet their daily cooking fuel needs through the portable biogas digester. Portable biogas digesters can provide economic benefits by reducing household fuel costs. Over time, these savings can affect the initial investment in biogas digesters. A study in Kenya found that using biogas for cooking saved households an average of 8.68 € per month. This reduces the need for firewood and prevents deforestation because of its positive effect in terms of climate change and the preservation of biodiversity. In addition, the use of the digestate as fertilizer enables a closed carbon cycle [55].

Based on the type and volume of the portable biogas digester, its capital cost varies from 37 to 747 €. For instance, in South Africa, Mutungwazi et al. [23] reported that an EZ biogas digester (portable digester) costs around 738 €. According to Ajay et al. [74], the capital cost for portable biogas digester capacity is generally approximately 280–373 €/m^3. Siddiq et al. [53] analyzed the feasibility of a portable biogas digester to produce household-scale energy. The study concentrated on analyzing the technical and economic feasibility by setting scenarios, the availability of cow dung, and the need for cooking gas and daily basic electricity based on the supply and demand side, respectively. The economic parameters used in the study include the Net Present Value (NPV), Internal Rate of Return (IRR), and Payback period (PBP). From the study's findings, the NPV was reported as 195, 620, and 979 €; IRR (32.30%); and 2.70 years of PBP. The portable biogas digester produced 2.247 m^3 of biogas every day.

9. Conclusions

The review has looked at the specific and important aspects of portable biogas digester designs. In this review, emphasis is provided on the modification of the biogas digester design and the need for a portable biogas digester. The design and assumption to be considered for the study, material for the portable digester, and economic feasibility were presented. It is found that most portable biogas digesters are made from plastic because they are light and have less weight as well as are not expensive. From the study, the design of portable biogas is often and usually modified from the fixed-dome, floating drum, and balloon digester, thereby enhancing its technical factor. While compared with other designs, the portable digester offers lots of advantages such as easy transportation, versatility to be customized, and adaptability to various settings. To seek to develop a low-cost and lightweight digester, portable biogas digesters are promising because of the characteristics they offer, which help increase accessibility and adoption, especially for family households. This could involve using locally available materials and simple designs that are easy to construct and maintain, as well as the development of mobile or modular digesters that can be easily transported and installed.

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