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Systematic review and meta-analysis

A systematic review of the design considerations for the operation and maintenance of small-scale biogas digesters

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ABSTRACT

This review investigates small-scale biogas digesters' design and construction considerations to address biogas digesters' failures shortly after installation. The frequent failures of small-scale or household biogas digesters negatively affect its adoption as a clean domestic cooking fuel in developing countries, affecting the achievement of Sustainable Development Goal (SDG) 7. The study considered Scopus database-indexed peer-reviewed journals published between 2000 and 2022. Selected papers focussed on real-time monitoring, stirring mechanisms, and temperature control systems based on predefined inclusion and exclusion criteria with initial search results of 4751 documents, narrowing to 55 papers. The PRISMA 2020 statement was adopted to conduct the study. The study highlights the importance of incorporating a real-time monitoring system as a design factor in small-scale biogas digesters for successful operation and maintenance. The study's findings may be helpful to practitioners, policymakers, and researchers promoting sustainable energy and waste management solutions in low-resource settings.

1. Introduction

Rapid population growth, urbanization, and generally enhanced living conditions globally are projected to come with a corresponding waste generation, which, if not properly managed, will pose a major disposal challenge [1]. Since 1960, the world's population has more than doubled, and by 2050, it will have more than tripled, reaching approximately 9.8 billion people and peaking at 11 billion in 2100 [2]. The expanding urbanization of humans and industries will generate waste that must be managed innovatively to prevent the adverse impact of improper waste disposal [3–5].

Approximately 2.01 billion tons of municipal solid waste (MSW) are produced annually, expected to increase to 3.40 billion tons in about 30 years. According to the World Bank, high-income nations will experience an increase in daily per capita waste of 19 %. In comparison, low and middle-income countries will experience a rise of 40 % or more. MSW consists of all the items people use daily, such as food packaging, clothing, bottles, leftover food, papers, electronics, and batteries. Despite all recycling technologies, less than 20 % of waste is recycled annually, while the remaining 80 % is disposed off in landfills. With approximately 18 % of the world's population, China is the largest producer of MSW, accounting for over 15 % of the total [6]. This major worldwide issue necessitates a paradigm shift in the design of waste management solutions that have high success rates and acceptability.

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Waste-to-energy technologies are receiving much attention globally as the technology promises waste management solutions and energy access [7,8]. Small-scale or household anaerobic digestion systems address the challenges associated with commercial/industrial waste management systems to manage the organic waste produced on-site to save on transportation costs and reduce the amount of waste sent to landfill sites [1]. The utilization of waste for energy generation could address the worrying trend of energy poverty from inadequate access to modern energy conversion technologies, notably in developing countries, that threatens the achievement of the Sustainable Development Goals (SDGs) [9–12]. The vulnerable population, primarily women and children, is exposed to harmful gases using crude conversion technology (direct combustion) for wood fuels.

Energy access has been the engine for industrialization in the developed world and a challenge in the developing world [13,14]. The international community's aspiration to reduce the dependence on fossil fuels due to their Greenhouse Gas Emissions (GHG) presents an opportunity and a challenge for the developing world. The primary constraint for developing countries is the political commitment, technology know-how, and financial strength to invest in clean energy sources' conversion technologies [15,16].

Biomass is a ubiquitous form of energy that forms a significant portion of energy source for domestic heating, especially in developing countries. Bioenergy conversion technology as a renewable energy source provides about three-quarters of the world's energy needs. It offers approximately 35–55 EJ, making it the most significant renewable energy source by a wide margin [17]. Biomass contributes less than 10 % of the energy supply in industrialized nations. However, in emerging countries, the share can reach 20–30 % [18]. The biomass energy resource is vastly underutilized in meeting the energy demands of these developing countries, mainly due to economic, social, and technological application challenges. Furthermore, inefficient conversion technologies are employed, limiting the optimum application of the resource [19–21].

From traditional to modern utilization of biomass, significant progress has been made in enhancing the efficiency and lowering the health risk of conventional exploration of biomass as a source of clean energy. Biogas is methane-rich, flammable gas produced through the decomposition of organic matter by microorganisms (fungi, bacteria, and decomposer organisms) in a moist, favorable environment. Humus and essential plant nutrients are by-products of organic matter decomposition. Microorganisms classified as either aerobic (in the presence of oxygen) or anaerobic (limited oxygen) facilitate the process of digestion of organic matter [22]. Additionally, aerobic digestion has minimal emission of $CH_{4,}$ and the gases released are estimated to be about eight times more potent GHG than CO_2 [23]. Feedstocks' anaerobic digestion (AD) (animal or plant matter) is a valuable energy supply process generally taking four stages. These stages are hydrolysis, acidogenesis, acetogenesis, and methanogenesis [24–28].

Varied designs have been constructed to harness biogas from feedstock digestion for domestic and industrial use [29–31]. Volatile solids (VS) content, biological (biochemical) oxygen demand (BOD), chemical oxygen demand (COD), carbon-nitrogen (C/N) ratio, and the presence of inhibitory compounds are some of the most crucial feedstock factors to consider in the digestion process. Feedstock parameters influence AD processes' performance, and so can numerous other factors, such as reactor design and operational conditions, either through process augmentation or inhibition [27].

Various types of biogas digesters are in operation worldwide, such as fixed dome, floating drum, puxin, balloon type, earth pit, ferro-cement, etc. Typically, there are two ways to complete an AD process: batch and continuous setup. In a batch-type reactor, a constant amount of feedstock is introduced into the digester, and the mass or volume remains constant for the hydraulic retention time (HRT). In a continuous-type reactor, fresh feed is delivered into the digester at regular intervals, while an equivalent amount of sludge is withdrawn simultaneously, maintaining a constant volume of sludge [32,33]. The biogas digester, also known as the biogas plant, is a simple structure (chamber) in which biochemical reactions occur in the presence of microorganisms to produce biogas under anaerobic conditions. Basic small-scale biogas digesters are fixed-dome plants, balloon plants, low-cost polyethylene tube digesters, horizontal plants, earth-pit plants, Ferro-cement, and floating-drum plants. There are variations of these basic types as improvements to the original designs [31,33–36]. For a digester to be classified as small-scale, house-scale, or portable, it depends on the volume of the digester. Household biogas digesters are easily operated, cost-effective, and can digest varied feedstock. However, this limits the quantity of feedstock to digest, intermittent biogas generation, and maintenance intensive. On the other hand, continuous large-scale digesters give the benefit of economies of scale and efficiency, hence continuous biogas supply. There are divergent views among published literature on the size of a small-scale digester. The sizes reported and classified as small-scale are typically volumes below 200 m^3 [1,32,37–42].

Biogas technology has been used over centuries and has seen improvement, notably in developed and some developing countries such as China and India; however, much is yet to be seen in the African continent [43,44]. The success of small-scale biogas digesters in these developing countries has been attributed to government support in the form of technical and financial assistance. It is worth noting that in the African continent, the story is not different as the introduction and promotion of biogas technology have been chiefly through governmental and non-governmental organizations (NGOs), though not much success has been recorded [45–47].

The biogas technology is not without problems, and investigations on the failure and low adoption of the technology have been attempted in reviews but mainly about feedstock, economics, socioeconomics, incentives, types of digesters, user perception of the technology, and policy challenges [1,29,31,36,38,43,44,47]. Meanwhile, developing a vivid picture of the scale of challenges facing the technology requires a wholesome consideration of evidence in the literature. However, considering the multidisciplinary nature of the technology, doing a wholesome review will be challenging to achieve; thus, there is a need to focus on specific sections of the technology, such as reactor designs and key parameters (temperature, stirring, biogas quality) monitoring.

Poorly designed digesters can result in numerous issues, including decreased biogas production, toxic gas accumulation, and system failures [40]. Several elements of the design and construction of anaerobic digesters can be modified to achieve the desired biogas yields. This study aimed to review literature regarding the factors considered in designing and constructing small-scale biogas digesters for effective operation and maintenance. Information from this work is needed to fill the knowledge gap necessary for the selection of reactor designs and appreciate how variable technological parameters impact the success of the small-scale biogas system.

2. Materials and methods

2.1. Study design strategy

To meet the research objective of this study, a comprehensive literature analysis was undertaken to provide comprehensive information on factors that inform the design and construction of small-scale digesters for smooth operation and maintenance.

The study adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) 2020 statement as updated by Page et al. [49]. The statement is universally recognized as a scientific strategy for performing systematic literature reviews. This technique of research summarizes and synthesizes the findings of existing literature on a particular research topic or field, allowing the opportunity to identify significant ideas, research gaps, forms of evidence to impact practice, and policymaking to guide future research [48,50,51]. It also emphasizes the scientific proof of the relationship between variables and reveals unexplored relationships [52]. In addition, a systematic review was used because of the specialized nature of the review's scope.

2.2. Electronic database identification and eligibility criteria

A thorough search of internet resources and relevant literature databases for biogas design and construction was conducted. It was done to discover peer-reviewed publications and journals that guaranteed data quality and reliability. The Scopus database was used because it features a rigorous indexing technique for documents, and retrieving bibliometric data is simple. In addition, academics have commented on the database's rigor, quality, and resilience, which contain a significant amount of data from other databases (Thompson Reuters, Web of Science, Google Scholar, Dimensions, etc.) [50–52]. The search results were exported as comma-separated values (.csv) files for Microsoft Office Excel processing.

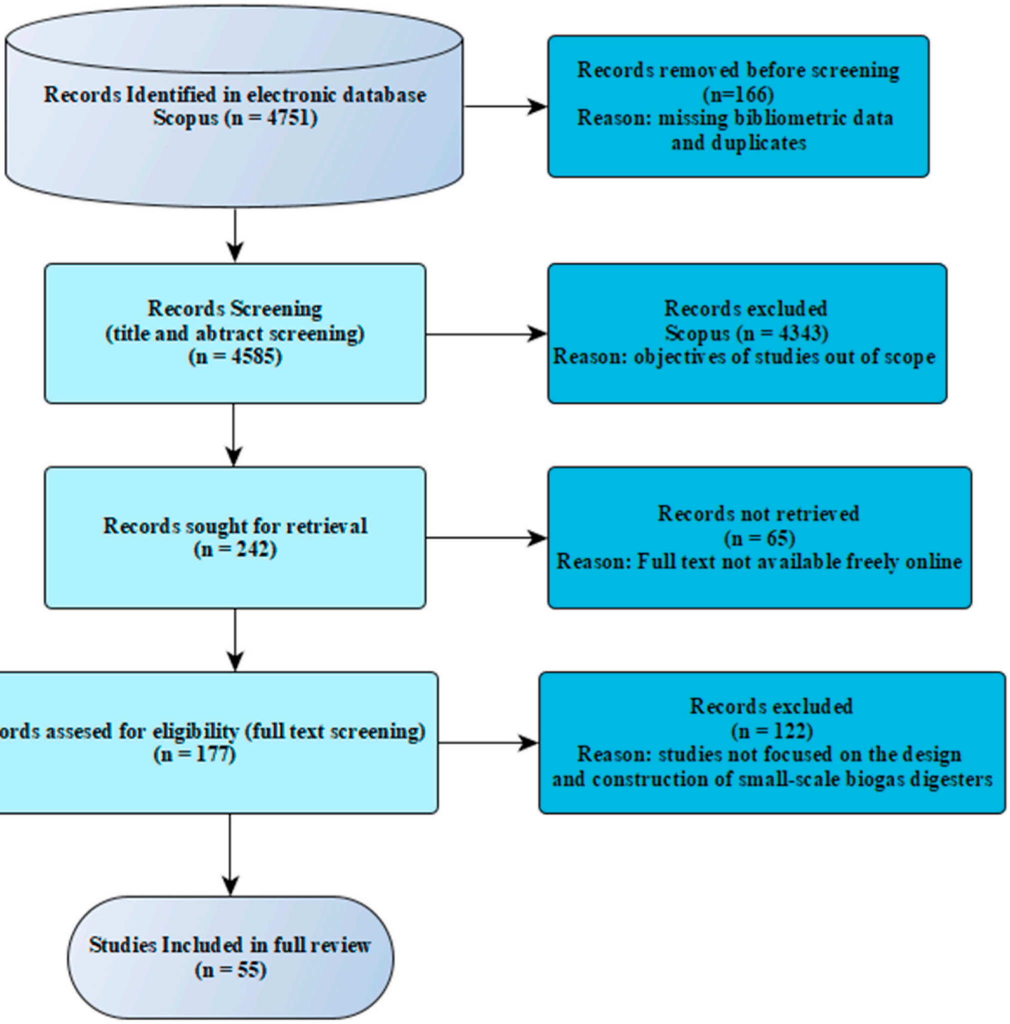

Fig. 1. Flow diagram of literature selection using PRISMA 2020 statement.

The eligibility criteria was developed to capture published documents (articles and conference papers) in English only. The time restriction on selected documents was from the year 2000–2022. Furthermore, considering the multidisciplinary nature of the study, no study area/subject field was specified in the search string.

2.3. Screening and selection of publications

An advanced search of the Scopus database (www.scopus.com) was performed using the article's title, abstract, and keywords. A comprehensive list of primary and secondary key terms was generated iteratively, connected with Boolean logic, and filtered to include as many relevant research articles as possible. Three independent reviewers screened the papers based on a predetermined checklist. The most frequently used search terms in the literature concerning the design and construction of small-scale biogas digesters served as the primary search terms. The search string utilized is displayed below.

TITLE-ABS-KEY (design OR construction OR "small-scale" OR "small scale" OR "on-site monitoring "OR "IoT" AND biogas) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, "final")).

2.4. Descriptive analysis of literature extracted

The search in the Scopus database returned 4751 documents. Three independent reviewers cleaned the extracted file and excluded 166 papers due to missing bibliometric data. A total of 4585 documents were left for the title and abstract screening, and 4343 articles were excluded. The remaining 242 documents' full text was sought for retrieval to determine their relevance to the objective of the study. The full text of documents successfully retrieved were assessed for eligibility, and 122 papers were deleted, allowing 55 for inclusion in the review. Fig. 1 illustrates the details of the literature included and excluded for the various stages of the work following the PRISMA 2020 statement. The article count distribution over the years (2000–2022) synthesized in the study is shown in Fig. 2.

The country-wise contribution of articles to the selected articles synthesized is displayed in Fig. 3. India is the most prolific contributing country, with eight articles, followed by China, with six articles. In the African continent, South Africa and Nigeria contributed three and four articles, respectively.

The co-occurrence network structure of frequently used keywords; Keywords are an essential indicator of the author's research interests and priorities in their study area. The keywords validate the extracted dataset about the objectives of the current study. Consequently, this study heavily relied on the author's keyword analysis. A minimum threshold of three (3) instances was established to evaluate a term in the Vosviewer software network diagram. The co-occurrence network structure of frequently used keywords is depicted in Fig. 4 as four (4) relevant clusters.

2.5. Literature categorization and data analysis items

The classification method utilized in this study focuses primarily on the design considerations of small-scale digester, temperature control, stirring mechanisms, and monitoring key performance indicators. The data was retrieved, analyzed, and discussed to identify gaps, develop consensus, and advance the recommended path of future research concerning the design and construction of small-scale biogas digesters.

2.6. Quality assessment approach

Indeed, evaluating the quality of the studies included in systematic reviews is one of the most crucial aspects of the studies. Also, for this reason, the quality of the included studies must be evaluated precisely using inclusion and exclusion criteria developed earlier in the study. By thoroughly checking with three independent reviewers against predefined inclusion or exclusion criteria, the quality of

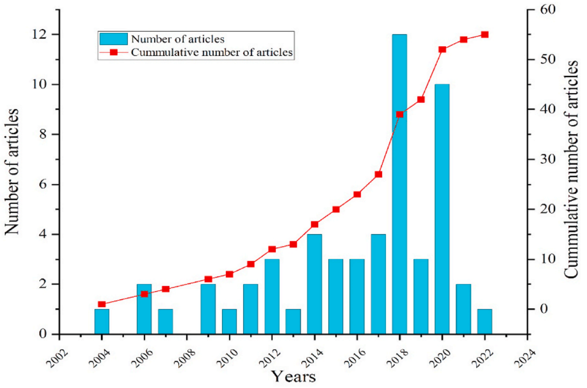

Fig. 2. Yearly distribution of articles (2000–2022), the cumulative number of publications.

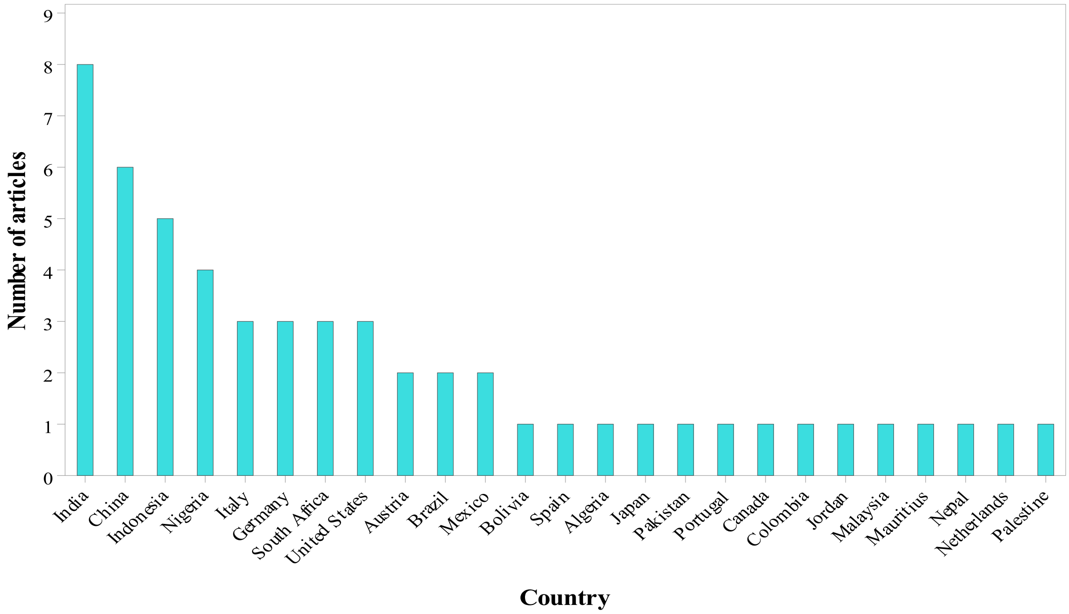

Fig. 3. Country's contributions to articles in the study.

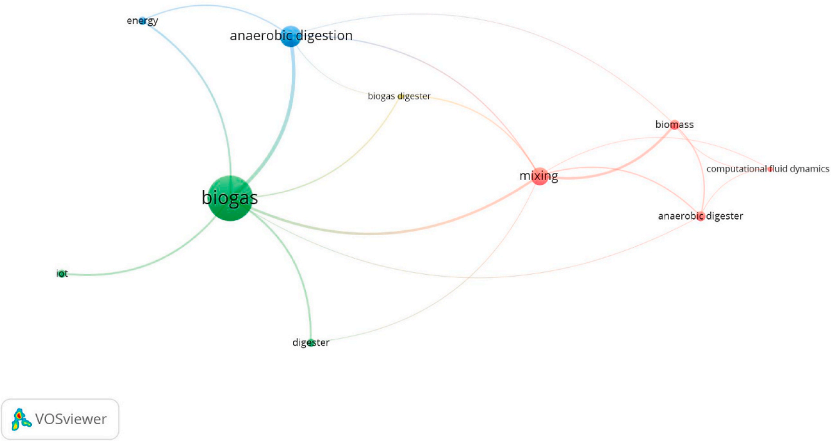

Fig. 4. Co-occurrence keyword network of author's keywords.

the review was not compromised.

3. Results and discussions

This study section presents the results and discusses thematic areas that reflect common design issues concerning biogas system failures. Table 1 summarizes the number of documents considered for each thematic area of the review.

Table 1
Number of articles for each theme.

s/n	Subheadings -themes	Number of documents
1	Design consideration for small-scale biogas digester	23
2	Stirring mechanisms for small-scale biogas digesters	15
3	Monitoring systems of small-scale digesters	7
4	Small-scale biogas temperature regulation strategies	10
	Total	**55**

3.1. Design consideration for small-scale biogas digester

Understanding household digester designs and proposed modifications can significantly improve the operation and adaptability of the systems. Insight into the type, size, material for construction, feedstock type, safety consideration, and economic viability are vital factors to consider in digester design. Modifying an existing biogas digester design requires identifying the areas that need improvement [42,53]. Varied approaches have been reported in literature, from increasing the size, improving the feedstock quality, or improving mixing ratios as solutions to biodigester problems. Synthesizing and understanding these proposed strategies is critical to developing a holistic image of the research efforts towards saving biodigesters and a base to direct future research significantly.

Previous reviews and research have demonstrated extensively the biogas yield from various feedstock and different digesters [39,42,54–59]. Furthermore, available literature suggests extensive work has been done on designing and fabricating small-scale biogas digesters, primarily implemented in developing countries worldwide. Low-tech designs, small sizes, portable designs, and the use of local materials in construction characterize these designs. Most designs are entirely different from each other without any systematic method for determining the sizes and shapes of digesters. The first attempt to develop a universal design methodology for a low-cost tuber digester was reported in the work of Marti-Herrero and Cipriano [60]. The significant contribution of small-scale tubular anaerobic digesters in promoting gender equity and mitigating deforestation is explored in the review of Kinyua et al. [61], emphasizing the crucial role biogas technology can play in attaining SDG 5 on gender equality.

However, the literature on the guidelines to enhance the deployment of the technology is scanty, as suggested by this study. Other authors have also proposed using software in the design of small-scale biogas digesters to provide an opportunity to assess the bioconversion of the systems before fabrication using SuperPro® Designer [62]. The results showed a reasonable agreement between the actual and predicted data from the simulation and were further bolstered by the economic analysis offered by the model [62]. Additionally, the parameters to be considered in designing a continuous flow laboratory biogas digester were determined using nine sets of bioreactors in batch and the German Standard VDI 4630 [63]. The data was then used to project the positive biogas production potential of feedstock.

Feedstock availability and quality have been challenging for biogas digesters, especially in large-scale biogas systems where large quantities of feedstock are required for digestion. Feedstock such as kitchen waste, night soil, and dairy manure has been used as the primary feedstock with digesters designed specially to digest them [64–74]. Feedstock choice as a cardinal factor in the design is emphasized in many studies that have prioritized it. As reported by several authors, the proposed designs for the digestion of feedstock suggest that readily available feedstock contributes significantly to the design of small-scale biogas digesters. It is worth noting that the choice of designs is varied, and there are no standard approaches for sizing, for checking the quantity of feedstock, hydraulic retention time, and digestion factors, making it challenging to compare biogas yields and select the best designs. Additionally, some studies considered co-digestion of feedstock as a strategy to enhance biogas production [70,71,75]. However, most of the studies were silent on the pre-treatment of feedstock, which is key to ensuring successful digestion.

Other designs have been based on the portability, availability of local materials, and cost. Kashif et al. [76] developed a modified floating dome-type digester to make it portable for rural Pakistan. Experiment tests confirmed the developed plant's functionality and biogas yield. The produced product is advantageous since it has a long lifespan, is lightweight, and can generate enough methane gas to meet household cooking needs. Emphasis on the portability of designs for application in densely populated areas was demonstrated by Ammar et al. [77] as a strategy to provide biogas for domestic cooking and waste management. Using locally available material to construct digesters can reduce the cost and hence the adaptability of the small scale as expunged by Refs. [78–80]. Currently, biogas digesters are constructed out of reinforced concrete or steel panels coated with glass enamel. Corrosion-resistant steels, plastics, and fiberglass are used to a limited extent. To safeguard reinforced concrete, a bituminous coating is applied to maintain structural integrity. The hydrophobic anti-adhesion coating of modern materials such as low-permeable EFE ultra+ and PFA uptra+ was investigated. The coating exhibited no color change, whereas the structural steel shed considerable mass [81].

The design of small-scale biogas digesters is mainly intended for converting waste to energy in rural areas to meet domestic energy requirements such as heating. These digesters are usually fabricated using materials that are available, durable, and easy to fabricate, such as mild and stainless steels, Styrofoam, polythene sheet, concrete tanks, fiberglass reinforced plastic, and other materials [78,82–89]. The conventional development and application of small-scale biogas reactors for rural settings are seeing new applications in urban centers for converting kitchen waste to biogas for domestic use, as reported in the literature [67,90]. It is insightful to note that the literature reviewed demonstrated increasingly the potential for the benefit of small-scale digesters in urban centers. It suggests that the application of small-scale digesters has the potential to argument the domestic energy needs of urban residents while contributing to sanitation management, as reported in the review of Rusin et al. [81]. However, key design considerations such as the safety of designs, generated biogas quality, and the safety of discharge or use of effluent from small-scale biodigesters were rarely considered in the literature. Furthermore, there were no reports of guidelines or standards in the design of small-scale biogas digesters, making it challenging to evaluate proposed designs, further hindering policy developments to promote the technology.

3.2. Stirring mechanisms for small-scale biogas digesters

The choice of stirring mechanism will depend on variables such as the size of the digester, the type of organic material being processed, and the budget [91]. The electrical energy demand of the stirrer system constitutes a significant portion of the total electricity consumption of a biogas plant, as measured by the biogas plant's electric power consumption. In large-scale biogas plants, the stirrer system accounts for a significant portion of the total electricity consumption [92]. Depending on the design, feedstock, and size of the digester, stirring mechanisms such as mechanical, hydraulic, pneumatic, and passive are employed. Some biogas digesters may also use a combination of these stirring mechanisms to promote mixing and enhance biogas production [91,92]. The optimal operation of biogas digesters hinges on several factors, and ensuring the digester is designed to operate with the best parameters is paramount. Evidence in the literature shows an apparent effect of feedstock mixing on digester operation [93]. Previous review studies suggest several reasons for the consideration of mixing mechanisms or agitators in the design of biogas digestors, some of which are to prevent stratification of feedstock, ensure uniform distribution of microorganisms, prevent scum formation, and maintain optimal operating conditions such as temperature, pH, moisture content in all parts of the digester [94,95]. Also, this review suggests that much of the work done in this area was computational fluid dynamics (CFD) modeling using various propeller/impeller heights, rotation angles, and orientations. Simulations done using the rheology of fluid reported in other studies showed conformity to the non-Newtonian generalized Ostwald-de Waele power law [93,96–106]. The mechanisms employed in these studies were either simulations or pilot scales with little evidence of scale-up implementation. It is not easy to ascertain workability without proof of results on scaling up from proposed mechanisms.

However, results from several studies on simulations and stirring showed a positive contribution to the operation of the digesters. Additionally, the efficiency of a submersible motor mixer and inclined agitator on the nutrient distribution of practical research biogas plants of Hohenheim University was carried out by Andreas et al. [107]. The research indicated that directly measuring nutrient distribution in a digester to optimize agitator performance is a promising strategy. The type of agitator and agitation regime substantially impacts the concentrations of organic acids, which are unrelated to the amount of dry matter. A slow-moving incline agitator with larger propeller diameters instead of a fast-moving submersible mixer with smaller propeller diameters could reduce electric energy consumption by as much as 70 % without sacrificing mixing quality. In contrast, a pneumatic-driven mechanism design with automatic and controlled pressure swing mechanisms incorporated by the gas production serves as the driving force for slurry circulation in the digester, promoting gas recovery and enhancing digestion efficiency [108].

The design of four-blade propellers to enhance stirring in various sizes of small-scale digesters has been demonstrated in several studies, which confirmed the significant impact of incorporating a stirring system in the digester [108–111]. Another study on pneumatic use in mixing feedstock in a laboratory-scale digester demonstrated the impact of partial mixing induced by gas upflow/recirculation in the digester using an internal draft tube. The results show that mixing has an apparent effect on digester operation. Without mixing, the performance of the digester degraded within 30–50 days, whereas mixing enabled continuous production of biogas methane [112]. Hydraulic and passive stirring mechanisms seem to be underexplored in the literature, which could be due to a lack of interest in research or fewer highlights to spark interest. Most studies focus on mechanical mechanisms, which have a major drawback of high energy consumption, making them uneconomical and unattractive for small-scale biogas digesters. It is also interesting to notice that research in the area has declined recently. The decline in published work in recent times would further worsen the acceptability of the technology due to persistent failures. This conclusion aligns with earlier studies about the effects of stirring mechanisms on small-scale biogas digesters [113–115].

3.3. *Monitoring systems of small-scale digesters*

Monitoring systems are essential for the efficient and effective operation of biogas digesters. Other review studies have shown the extensive research and use of monitoring systems in large-scale biogas digesters to manage and ensure system stability [55,116–118]; much is yet to be seen in small-scale digesters. Monitoring systems help to optimize digestion, detect problems early, improve energy efficiency, ensure compliance with regulations, and enhance safety. The authors of previous reviews assert that the absence of monitoring systems for preventive and corrective maintenance of the digester system is one of the most significant factors contributing to digester failure. It was also noted that biogas production systems can be more efficient and reliable through proper monitoring and maintenance [119–121]. Traditional laboratory analysis of digester sludge can provide valuable insight into the fermentation process, but it can be time-consuming and may not provide real-time data. On-site monitoring methods can help overcome these limitations and provide operators with real-time information about the fermentation process, enabling them to optimize the operation of the digester and enhance biogas production efficiency [122,123].

The finding of this study suggests that there is limited literature on monitoring systems for physio-chemical parameters for small-scale digesters, especially in developing countries where there are reported cases of failures of the system.

Methane in digesters is flammable and harmful when openly released into the atmosphere. The study by Feng Wang [124] demonstrated that simulation data from the Unified Dispersion Model can be used to develop an empirical model for predicting the effects of gas leakage. A real-time monitoring early-warning system was developed to prevent accidents and ensure safety using an incident database, hazard and operability analysis (HAZOP) analysis, numerical simulation, consequence quantitative calculation, and emergency response guidance. Another study assessed the efficacy of common early warning indicators (including CH_4, CO_2, H_2S, volatile fatty acids (VFAs), alkalinity (ALK), total ammonia concentration (TAN), and free ammonia concentration (FAN)) in monitoring the instability of the anaerobic digestion process at a practical engineering plant. The results demonstrated that the various indicators could not provide an adequate early warning before the digester failed and collapsed [125].

Internet of Things (IoT) technology has been the dominant technology among authors to monitor and control various operating parameters of digesters, reflecting the current revolutionizing potential of the technology. In the study of Anubhav Gupta [126], pH, water level, and consumption of biogas were monitored using an Arduino Mega ESP8266 microcontroller with sensors (waterproof LM35, pH sensor module V1.1, ultrasonic sensor, and solenoid valve) to measure the parameters understudy. The study's finding was innovative as the proposed architecture offered real-time monitoring of parameters to ease the operation and maintenance activities. Additionally, an Esp8266 Arduino Module microcontroller with two temperature sensors (for the top and bottom of the digester) and a gas detector powered by a solar-charged battery in Rwanda was prototyped using IoT technology. The system's workability was

Table 2
Summary of literature on the temperature control strategy of small-scale biogas digesters.

Title/Reference	Aim of study	Type, size, and feedstock of digester	Temperature control strategies	Temp achieved	Study Country	Results	Limitation of study
Design and Sizing of a Digester Coupled to an Air Solar Collector [139]	A feasibility study for constructing a 15 m³ family digester coupled with an air solar collector.	Indian Model - floating bell/15 m³/cow dung	A low-temperature heating system for air utilizing 20 m² of solar collectors with stone bed seasonal storage	40 °C	Algeria	Produce between 68.4 and 185.4 m³ of biogas depending on the digestion temperature. Equivalent to three standard butane gas cans (13 kg per can).	The design did not consider a mechanism to ensure the even distribution of heat in the digestion enclosure.
Design of Solar-Assisted Community Biogas Plant [140]	This study aims to remedy the difficulty of biogas production in cold weather conditions.	15 m³/ feedstock not specified	Flat plate solar collector with thick insulation	35 °C	India	Based on the numerical database, it can be concluded that solar-assisted biogas plants have a promising future in cold regions.	The working fluid (water) is used to heat the wall of the digester without a mechanism to distribute the heat evenly. The study did not conduct field validation of the generated equations.
Use of a Portable Greenhouse for Temperature Control in a Small-scale Biogas Production Unit [143]	To design a 100 ℓ agitated portable carbon steel digester housed within a Greenhouse.	Portable/0.1 m³/Cow dung	Greenhouse was designed with a double layer of polyethylene plastic	34°C–36 °C	South Africa	A specific biogas yield of 0.036 m³/kgVS was added, and an enhanced methane yield of 55 %, which is more significant than the 50 % attained by other digester designs. The preservation of a limited temperature range	Greenhouse temperature stratification control was not considered in the design.
Conceptual Design and Functional Modelling of a Portable Thermophilic Biodigester for a High Dry Matter Feedstock [141]	Utilizing sheep manure to create a conceptual engineering design for a portable biodigester	Portable/10 m³/Sheep manure	Container thermal insulation and warm Water heated by solar energy	Not specified	Mexico	The operation and safe functioning of the biodigester enables a more efficient energy balance, resulting in savings of up to fifty percent for the decentral scheme, compared to the central energy generation for the entire process.	The study did not present the integration of solar heating systems, and details of the insulation used were not provided. The issue of temperature distribution in the system was not discussed.
Pilot-scale anaerobic digester for enhanced biogas production from poultry manure using a	This study seeks to identify the critical operational parameters required to design and install a farm-scale	0.5 m³/20 % poultry manure co-digested with seed material	Low-cost solar water heating system with heat exchangers and stirring mechanism	40 °C	Palestine	Total biogas production was 39.95 m³, and the methane content It was ranged between 46 % and 68 %.	The work did not consider the design challenges for more giant digesters. Insulations were not considered.

(continued on next page)

Table 2 (*continued*)

Title/Reference	Aim of study	Type, size, and feedstock of digester	Temperature control strategies	Temp achieved	Study Country	Results	Limitation of study
solar water heating system [142]	anaerobic digester utilizing chicken manure.						
Evaluation of the low technology tubular digesters in the production of biogas from slaughterhouse wastewater treatment [148]	To determine the operational conditions and performance of low-cost tubular digesters that generate biogas from slaughterhouse wastewater treatment.	Tubular/3 m^3/ slaughterhouse wastewater	Passive solar heating	27 °C	Bolivia	Solar heating increased the temperature by three more than the ambient temperature.	The temperature was taken from a depth of 1 m. Due to the lack of an active system for temperature circulation in the design, the impact of a passive solar heater might not be entirely practical.
Design of the Solar Energy-Heated Biogas Digester [149]	To design a solar energy-heated biogas digester is to create a facility that radiates heat from solar thermal energy to maintain the biogas digester's temperature.	household/ 0.88 m^3	Solar heated with insulation and heat exchanger to stabilize temperature during the day	35 °C	China	The solar energy-heated biogas digester system is designed to divide the traditional biogas digester into three parts, decrease the heating volume and the heat dissipating surface, and save energy.	No stirring mechanism was discussed to ensure an even distribution of heat.
Affordable solar-assisted biogas digesters for cold climates: Experiment, model, verification, and analysis [80]	To investigate the thermal performance of affordable bio-digesters solar-assisted	Plug flow digesters/2.5 m^3	Agrofilm (transparent), Geomembrane, and LDPE (Low-Density Polyethylene) (Blue) Tube material for greenhouse with insulation	Agrofilm (clear) = 12.9 °C Geomembrane = 10 °C and LDPE = 6.9 °C Over ambient temperature	Peru	The material with the best thermal performance is transparent, so the sun's radiation can penetrate directly into the slurry. Also effective are heavy, dark fabrics. Thin, opaque substances (such as blue LDPE plastic) perform the worst.	Slurry and greenhouse temperature stratification were not addressed.
Development of a 3-D anaerobic digester heat transfer model for cold weather applications [147]	Utilizing a three-dimensional mathematical model to simulate heat transfer in anaerobic digesters under cold weather conditions and optimizing the various geometrical parameters to minimize heat losses.	Plug flow digesters	Insulation	Not specified	Canada	The cylindrical digester with a flat top provides the optimal geometry for minimizing heat losses in cold weather applications, and the heat-loss-biogas heat ratio (HLB) is a crucial parameter for describing	It is imperative to validate the model against experimental data to ensure its accuracy and dependability, as the model depends on the accuracy of the input data and assumptions made in the model.

(*continued on next page*)

Table 2 (*continued*)

Title/Reference	Aim of study	Type, size, and feedstock of digester	Temperature control strategies	Temp achieved	Study Country	Results	Limitation of study
						digester operations in cold weather climates.	
Design of A Solar Thermophilic Anaerobic Reactor for Small Farms [150]	To design for anaerobic treatment of liquid cow manure under thermophilic conditions (50 °C) by mounting a solar heating system on the reactor's roof.	10 m^3/cow manure	The solar-heated system has heat recovery units and an auxiliary heater. Insulation cover	50 °C	Netherlands	The simulation results indicate that the nighttime temperature fluctuations of the reactor are less than one °C, which is insufficient to inhibit microbial activity.	Considering the design is a simulation, there is a need for the authors to include the economic implication of their design, as cost is critical to the implementation.

confirmatory, and data was analyzed to aid in re-engineering the structure of a biogas digester for the Rwandan context and for research purposes to improve its performance efficiency and cost reduction [127].

Furthermore, IoT was used to measure the volume of gas produced in a digester. Data from the measurements of a flow meter was then transmitted to the ThingSpeak IoT platform. The biogas production volume was determined by processing the flow meter's flow rate measurement data. The Arduino Uno microcontroller with SIM800L, SD card module, Flowmeter FKHSC Digmesa, and real-time clock (RTC) were in the system design to achieve the study's objective [128]. Further advance in the design of monitoring systems is the addition of an Android platform developed to monitor pH, temperature, gas pressure, and total gas produced and consumed using an Arduino board and a GSM module to support IoT [129]. Arduino boards have been popular in monitoring systems for biogas digesters with the Esp8266 Arduino Module. It is also insightful to note that none of the studies considered the composition of the generated biogas, which is key in evaluating the quality and suitability of the biogas for use. In addition, measuring one or two operating parameters of the system might lead to inconclusive decisions in troubleshooting system faults. Other standalone monitoring systems identified in the study included the analysis of biogas using a Gas Chromatograph (CG) with a Flame Ionization Detector (FID) to separate methane and carbon dioxide [130].

The limited studies on the monitoring systems of small-scale biogas digesters suggested by this study agree with the findings of earlier review works [131–133], highlighting the need for further investigation to advance the success and adoption of household biogas technology.

3.4. *Small-scale biogas temperature regulation strategies*

Temperature control is a critical factor in the performance of biogas digesters as it affects the rate of biogas production, microbial activity, and overall process stability. Generally, the optimal temperature range for biogas is between 35 and 40 °C (95 and 104 °F). Temperatures below 20 °C (68 °F) or above 55 °C (131 °F) can significantly decrease the rate of biogas production. At lower temperatures, the activity of the microorganisms slows down, reducing the biogas production rate. At higher temperatures, the microorganisms can become stressed and may even die, leading to a complete shutdown of the biogas production process [134–137]. Various authors have proposed strategies for controlling the temperature in small-scale digesters [42,138]. The results and discussion presented are along the lines of the type of insulation used, heat exchangers, and heating systems adopted to achieve optimal operating temperatures for the digesters. Depending on the operating region of the digesters, the strategy for temperature control is varied, which can be seen in the proposed interventions of the authors.

The identified literature on temperature control in small-scale biogas digesters in this study indicates that the use of solar energy systems to manage the operating temperatures of digesters in cold regions is feasible and has a positive energy balance as it is renewable. The temperature of the slurry is influenced by various factors such as solar intensity, the water flow rate through the pipe, the number and size of collectors, and heat transfer coefficients between the wall, base, and ground. Sadek et al. [139] designed a low-temperature solar air-heated system where hot air circulates through a bed of stones surrounding the digester, causing thermal seasonal storage due to heat transfer from air to stones. This system allows the recovery of accumulated heat during cold periods to heat the digester. On the other hand, water as a working fluid in solar-assisted heating system design proposed by Ankit Gupta [140] based on the numerical database generated concluded that solar-assisted biogas plants have great potential for use in cold and hilly regions. Furthermore, a conceptual design of a portable thermophilic digester using hot water heated from solar energy demonstrated that the integration of additional renewable energy devices for the operation and safe functioning of the biodigester enables a more efficient energy balance, resulting in savings of up to 50 % for the decentral scheme, compared to the central energy generation, for the entire process [141]. The study did not provide information to support its claim on integrating solar-heated water into the biogas digester. Rowayda et al. [142] designed a pilot-scale digester to operate under mesophilic process conditions with a low-cost solar water heating system installed to increase biogas production in the digester for a poultry farm in Palestine equipped with a stirrer to ensure even temperature distribution. The greenhouse effect was used by Asheal et al. [143] to regulate the temperature of a small-scale portable biogas digester. They accomplished this by using an electronic circuit to control ventilation through an appropriately sized window and insulating the digester with a double polyethylene plastic greenhouse covering, creating an air film between the layers. Summarised in Table 2 are strategies proposed by authors and gaps that require further research. It is worth noting that solar energy use to heat digesters has received much attention. However, using heat exchangers powered by electricity has not seen much interest, probably owing to the cost implication, reliability of electricity supply, and technical complexity of such systems. The finding of this current study supports previous studies of [144–146] that small-scale biogas digesters frequently employ non-electric heat exchanger technologies, such as water or air-based heat exchangers. These alternatives are less complicated and costly to install and maintain, making them more suitable for small-scale operations. The work also found that temperature management requires additional design considerations that would further increase the construction, operation, and maintenance cost of small-scale biogas digesters. Studies on adopting passive systems, such as the insulation of digester walls, need attention. A single paper was found in the available literature concerning in-depth insulation geometry [147], suggesting limited works on the impact of insulation in managing temperature in biogas digesters.

3.5. Improving operations of small-scale digesters with artificial neural networks (ANN)

Emerging tools such as ANN are vital in improving small-scale biogas digesters' operation and maintenance. In contrast, the benefits of large-scale biogas digesters, such as the high capacity to process and generate large volumes of biogas, benefit from economies of scale [151]. Small-scale or household digesters promote localized, flexible, cost-effective feedstock digestion for biogas generation. The benefits derived from small-scale digesters have sparked interest in developing countries where high cost, complexity of operation, and stringent environmental regulations are challenging to meet for large-scale biogas digesters. ANN-based models have demonstrated in case studies the ability of the tool to develop advanced control strategies to predict faults and improve effluent to meet stringent environmental regulations. A study combined the generated ANN model with a genetic algorithm to maximize the methane concentration to 70 % of the total gas generated [152].

Integrating Artificial Neural Networks into digester operations holds immense potential. These networks enable process optimization, predictive maintenance, and real-time monitoring, improving efficiency and sustainability [153]. Using modeling and simulation studies, we may develop anaerobic digestors for sustainable waste management and renewable energy production, contributing to a cleaner, greener future.

4. Conclusions

Anaerobic digestion of biomass to generate biogas in household digesters can contribute to waste management and clean energy access. The technology, although old, still has challenges that hinder mass adoption. Highlights from the findings suggest that, although there is extensive literature on the design considerations for small-scale digesters, key design considerations such as the safety of digester designs, generated biogas quality, and the safety of discharge or use of effluent from small-scale biodigesters were rarely reported in the literature considered. Furthermore, there were no reports of guidelines or standards being followed in the design of small-scale biogas digesters, making it challenging to evaluate proposed designs, further hindering policy developments that promote the technology.

5. Limitation of study

The methodology adopted for this study has suggested insightful findings and conclusions; however, limitations are worth noting. The choice of database (Scopus) for the review inherently excluded studies not indexed in it, such as websites, blogs, social media, etc., which could have valuable information to contribute to the study. A study involving more than one (1) database could further advance the review.

6. Future agenda

Further studies should consider the development of standards to guide the design of digesters to adhere to best practices. Issues of acceptable quality of generated biogas and safe discharge or use of effluent need further research. The exploration of research into passive stirring mechanisms and temperature regulation of digesters in other studies would immensely increase the advancement of the technology. Insights into digesters' operating parameters would enhance digesters' operation and maintenance via a real-time monitoring system leveraging existing telecommunication infrastructure. Future studies on the design of small-scale biodigesters should consider exploring sensors in monitoring digesters to minimize system failures.

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Authorship roles

The corresponding author, Mubarick Issahaku, conceived and designed the systematic review, conducted the literature search and screening, analyzed and synthesized the data, drafted the manuscript, and prepared it for submission. The research supervisors, Nana Sarfo Agyemang Derkyi (PhD) and Francis Kemausuor (PhD) provided guidance and oversight throughout the review process. Participated in the literature search and screening, contributed to the data analysis and synthesis, and reviewed and approved the submission of the final manuscript.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Mubarick Issahaku: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nana Sarfo Agyemang Derkyi:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis. **Francis Kemausuor:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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