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# The Selection of Biogas Plants in the Indian Context Based on Performability—An Analytic Hierarchy Process and Weighted Aggregated Sum Product Assessment Approach

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**Abstract:** The purpose of this research paper is to present a framework for selecting a biogas plant for the Indian rural community, considering performability factors such as reliability, quality, maintainability, safety, and sustainability. This will ensure that the plant operates reliably, efficiently, and safely over its entire life cycle and can play a significant role as a decision-support tool for decision-makers (e.g., managers, engineers, stakeholders). The proposed framework integrates the Analytic Hierarchy Process (AHP), and the Weighted Aggregated Sum Product Assessment (WASPAS) to optimally evaluate and prioritize the best alternative based on performability factors. The findings show that the suitable biogas plant in the context of the Indian rural population is a fixed-dome-type plant. The decision-making process in selecting the best biogas plant can be effectively aided by using this suggested tool. Currently, there are no proper tools or methods for selecting biogas plants for rural areas due to a lack of data or relevant literature on operational issues. The proposed method uses performability factors for the selection, which has not been researched so far. Moreover, the AHP–WASPAS approach offers a robust method for selecting biogas plants, ensuring efficient and sustainable energy production. The proposed method will help policymakers and stakeholders to choose the best biogas plant in the context of Indian rural application.

**Keywords:** biogas plant; performability factors; WASPAS; AHP; MCDM



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## 1. Introduction

Biogas plays an important role in the field of energy, agriculture, and the environment by directly contributing to achieving SDG-7 (Sustainable Development Goal) and indirectly contributing to several other SDGs. Biogas not only boosts the economy of renewable energy with new job opportunities but also combats the climate crisis and contributes significantly to waste reduction [1]. Biogas production is a sustainable process that entails the breaking down of organic matter, including agricultural, animal, and sewage wastes, by microorganisms, mainly bacteria in the absence of oxygen. This process, known as anaerobic digestion, produces biogas, which is mainly composed of methane ($CH_4$) and carbon dioxide ($CO_2$), along with small amounts of other gases like hydrogen sulfide ($H_2S$) and ammonia ($NH_3$).

The generation of biogas provides numerous environmental benefits. The process helps to capture the greenhouse gases that would otherwise be discharged into the atmosphere. Biogas is utilized as a renewable energy source for cooking, heating, and generating electricity, thereby reducing dependency on fossil fuels.

Biogas production begins with the collection and blending of organic waste with water to prepare feedstock and feeding it into a digester, i.e., a biogas plant, in which the feedstock is broken down by bacteria in an oxygen-free environment. The biogas produced can be stored and used as needed, while the remaining digested material, known as digestate, can be used as a nutrient-rich fertilizer. The uses of modern bio-energy are anticipated to grow from 5% in 2025 to 16% of worldwide final energy consumption by 2050, as shown in Figure 1 (International Renewable Energy Agency [2]).

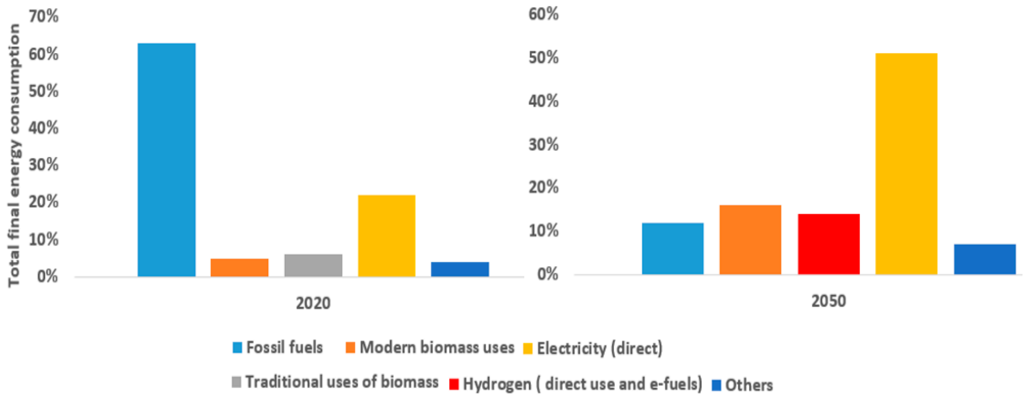


**Figure 1.** Total final energy consumption by energy carrier from 2020 to 2050 under the 1.5 °C scenario; TFEC = total final energy consumption; OECD (Organisation for Economic Co-operation and Development).

Despite several advantages, bio-energy is not yet widely used in rural regions. The Indian rural region, which is located outside the townships with limited access to domestic fuel and energy but with a greater focus on agriculture and landscapes, generates a variety of biogas feedstock substrates such as animal manure, agricultural residues, and energy crops. It is observed that more than 70% of the total biogas generation in India comes from animal manure, while about 15–20% of the total agricultural residues available in India are currently being used for biogas generation. This shows that there is significant potential to use agricultural residues for biogas production in the country. In addition to this, energy crops like sugarcane and maize are being grown for biogas production; however, there is limited potential as these are dominantly cultivated as food crops, and their economic viability for use in biogas generation is not fully realized. On average, 10 kg of animal manure can produce approximately 1000 L of biogas using the most efficiently controlled anaerobic digestion. Despite these promising resources, India produces 2.07 billion $m^3$/year of biogas, which is significantly lower than the projected potential.

A study was conducted to identify both technical and non-technical barriers to impending biogas dissemination in India. Several studies have been conducted to identify barriers to the adoption of biogas technology. The variations in numerous factors such as technology development, feedstock availability and quality, supply chain, legislative support, and public awareness were identified as the barriers to the significant development of biogas production in rural India [3,4]. Another study concluded that, in addition to technical expertise, improvements in social, political, and human behavior were necessary for the successful development and management of biogas technology, recognized high installation and maintenance costs, poor workmanship, and a lack of training as obstacles hindering the widespread adoption of biogas technology in rural India [5–7]. Issues such as feedstock shortages and the slow anaerobic digestion of animal manure can, however, be overcome by the co-digestion of different organic feedstock.

Extensive research has been conducted on food waste as a feedstock for anaerobic digestion, primarily due to its availability and suitability for the process. A community-scale biogas plant in educational institutions to generate biogas from food waste has been found to be a practical solution when quality and feed rate are properly monitored [8]. Significant research efforts have been dedicated to addressing barriers in rural communities and enhancing the technology and dissemination of biogas systems. These studies aim to promote the sustainability of biogas plants by focusing on improving feedstock-to-energy efficiency. In an attempt, research work has been conducted to investigate the impact of single and co-digestion of diverse feedstock on the energy balance of biogas systems [9].

There are numerous studies on the failure, risk, maintenance, and reliability aspects of engineering and natural systems [10,11]. Similar studies are limited in biogas production. For instance, performability analyses including reliability and safety assessments based on expert judgments were carried out for Arctic operations and offshore facilities [12,13]. Similar methods should be implemented for sustaining the operational safety of biogas plants. Due to the frequent occurrence of accidents in biogas facilities, it was necessary to develop failure diagnostic tools such as fault tree analysis (FTA) to help evaluate risk. An FTA-based study was employed to evaluate the overall risk of biogas plant [14]. Similar work on biogas plants is minimal.

In Latin America, several design options have been adopted to enhance the production of biogas by remarkably upgrading the operational characteristics that incorporate improvements in feedstock supply, transportation connectivity, and material availability [15]. A thorough system review must adopt a comprehensive approach, considering not only high dependability but also sustainability that completes an assessment of the performability. The performability factors are represented in Figure 2. By optimizing these factors, better design alternatives for the biogas plants can be achieved [16]. It is therefore essential to consider performability factors for the selection of biogas plants. The proposed method in this work reports this issue from the Indian perspective.


**Figure 2.** Performability factors.

There have been numerous research attempts to solve selection problems in engineering, science, and technology using Multi-Attribute Decision-Making (MADM) based on various design, operational, and environmental factors [17]. Multi-Criteria Decision-Making (MCDM) tools are simple and effectively applied tools for solving selection problems. Similar work on a selection of biogas plants based on performability factors has not been yet published using MCDM tools. The selection of biogas plants based on performability will ensure that the plant operates reliably, efficiently, and safely over its entire life cycle, and it can play a significant role as a decision-support tool for decision-makers (e.g., managers, engineers, and stakeholders). The objective of this study is to develop a framework to help select appropriate small-scale biogas plants based on performability attributes, using a combination of AHP and WASPAS methods.

The purpose of using this hybrid tool is to ensure consistency and accuracy in the decision process. The application of AI and ML tools is limited for the selection of biogas plants due to a lack of consistent and quality data, and, hence, the proposed MCDM tools are best suited for the selection of biogas plants for rural applications.

## 2. Overview of the Types of Biogas Plants Considered

In general, there are three basic models of biogas digester plants employed for domestic application: fixed-dome, floating-drum, and flexible-bag biogas plants (balloon). A recent addition to the above models is a two-stage biogas plant that is designed to overcome the productivity limitations of anaerobic digestion but at the cost of capital and operational costs [18]. Figure 3 represents various types of biogas plants generally employed in rural India, whether for domestic use or industrial application. In general, rural regions would reap benefits from biogas production as there is an abundant supply of feedstock. Countries like India, which boasts the largest rural population and vast agricultural land, have huge potential for biogas production and consumption. The Ministry of New and Renewable Energy (MNRE) (formerly known as the Ministry of New and Renewable Energy Non-Conventional Energy Sources) of the Government of India approves three types of family-sized biogas plants: floating-, fixed- and flexible-bag-type biogas plants [19]. These plants have their own performability characteristics, i.e., some plants have better safety while others exhibit high maintainability or have poor process quality. It is therefore essential to select appropriate plants based on performability factors for optimized design and operation.

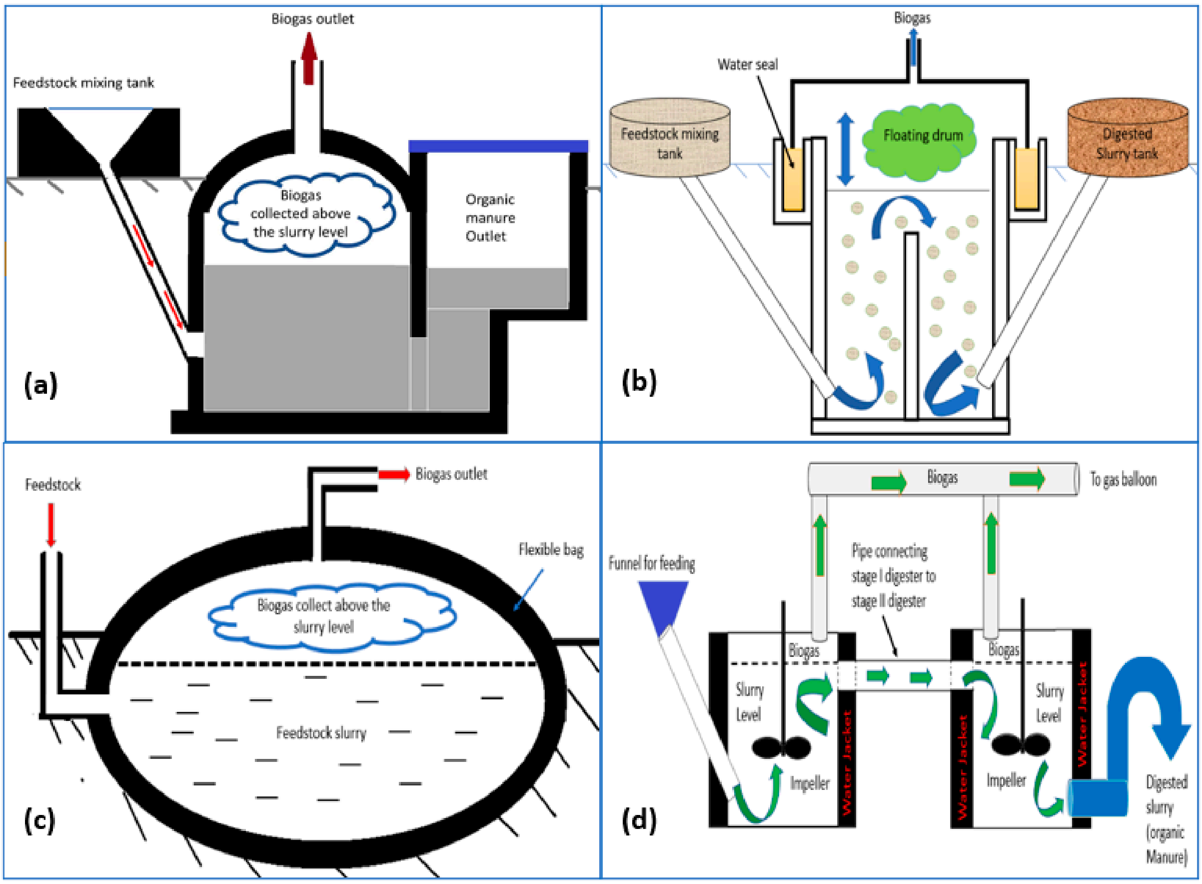


**Figure 3.** Different types of biogas plants used for domestic biogas plants: (**a**) Fixed-type biogas plant, (**b**) Floating-type biogas plant (**c**) Balloon-type biogas plant (**d**) Two-stage biogas plant.

A fixed-dome biogas plant has a stationary enclosed structure. A digester and a permanent, stationary gas holder lie atop the digestion in a fixed-dome biogas system. Gas production pushes the slurry into the outflow tank. The amount of biogas collected and the variation in surface elevations of slurry in the outflow tank are directly proportional to the increase in gas pressure. A biogas plant is constructed below ground, which protects it from physical harm while also saving the area. During winter nights, the underground digester is protected from the cold. In the summer, though, buried digesters warm very slowly, and they are reasonably priced. There are no moving components, so it is straightforward. The lack of steel parts extends the plant's life to 20 years or more. All concrete structures are long-lasting investments. To prevent the leakage of gas from the dome, masonry constructed out of brick or concrete is plastered. The generated biogas is collected in the upper part. Gas pressure increases with the volume of gas stored and is exerted on the slurry, which is pushed into a displacement chamber. Among the models approved by MNRE, the most popular are the floating domes (Khadi and Village Industries Commission type) and the fixed domes (Janata and Deenbandhu types). The Janata digester is cylindrical in shape, while the Deenbandhu plant is made up of two hemispherical parts. The materials used for constructing these types of biogas plants are readily available bricks and sand–mortar cement. The major disadvantages of fixed-type Janata plants are (i) the short-circuiting of the digested slurry reducing hydraulic retention time (HRT) to less than half of theoretical HRT; and (ii) the large gas pressure fluctuation for a small, accumulated gas volume. The Deenbandhu succeeded the Janata type with a 31.2% lower construction cost, achieved by an optimized surface area [20–23]. Low gas output due to insufficient feeding results in low pressure, which is insufficient to completely discharge the slurry from the outlet chamber. The effectiveness of gas utilization is reduced by fluctuations in gas pressure.

In a floating-type biogas plant, a gas holder acts as a gas pressure regulator to maintain the gas pressure constant. Animal and human wastes, as well as agricultural wastes, can be fed to both fixed-dome and floating-dome types. Fibrous agricultural wastes can also be used as an input feed. The use of whole fibrous substrates in a floating-type biogas plant will cause the gas holder to become entangled with floating scum. This leads to the irregular movement of the gasholder, resulting in fluctuations in gas pressure. Fibrous substrate should be chopped or ground into smaller particles, which helps in faster digestion and produces more gas. There are several studies that investigated the performance of biogas plants that use food wastes and lignocellulosic feedstock [24,25]. A Deenbandhu plant is more crack-proof and uses less building material. In one attempt, a comparative performance evaluation was conducted on Janata and Deebandhu plants that used dairy manure. It was concluded that the gas production rates of the Deenbandhu were both high [26].

Another advantage of this model is that the steel holder is completely leakproof and supplies biogas at constant pressure. However, the cost of a stainless-steel floating drum is high. Steel parts are susceptible to corrosion, which reduces the life of the drum to 3 to 12 years. The regular painting of steel parts to avoid corrosion increases maintenance costs. The flexible-bag biogas plant has the shortest operational lifespan (2 to 5 years), followed by the floating type (3 to 12 years) and the fixed-dome type (15 to 20 years), respectively. Materials and maintenance costs are high for floating biogas digesters and are the least for the tubular type, which costs around USD 300 to 1400/cu.m. The construction cost of the tubular type is USD 14–48/cu.m, while it is USD 80 to 670/cu.m. for the fixed type. Comparatively, floating-type biogas plants are easy to repair. Fixed-type biogas plants are vulnerable to cracks that require highly skilled workers for repair and reconstruction. Inorganic solids like dirt present in the feedstock are indigestible by the anaerobic bacteria. This dirt accumulation reduces the efficiency of the biogas plant. To improve its efficiency, thorough cleaning of the digester tank from the inside is required every 5 years for fixed-dome-type biogas plants [3]. Ultimately, this emphasizes the importance.

Balloon-type biogas plants consist of a digester bag made from plastic or rubber, in which the gas produced is collected at the top. To achieve the appropriate pressure required by the biogas appliances, sandbags are placed on the top. It is simple and quick to install, but it is not popular because of its short life. Moreover, the balloon material is not easily available. Other causes for the infamous balloon-type plant are low gas pressure, sensitivity to fluctuation in ambient temperatures, leakage from the main joint after a year of operation, increased risk of mechanical damage, frequent lowering of the feeding funnel, and blockage at the funnel's neck. Biogas production from the rubber balloon facility is reduced by 77%, while the Deenbandhu plant is reduced by only 16%. The rubber-balloon plant is not ideal for hilly places in general, although it may be suitable in mild-winter coastal areas or in areas where building a fixed-dome plant may be difficult, such as in areas with water-logged soil. Furthermore, the moisture content of the gas produced from the rubber-balloon plant turned out to be 43%, which is greater than that of the Deenbandhu plant [27].

A continuously stirred two-stage digester configuration is the most common type of configuration. It is suitable for wastewater, food waste, and high-solid substrate plants. The two-stage digester can produce 30% more biomethane than a single-stage reactor. However, the two-stage digesters are economically viable. The advantage of a two-stage reactor is that it provides a retention period of 10–18 days, which permits a 25–45% reduction in reactor size [27].

## 3. Performability Factors

Performability is an attribute that can be used to evaluate the performance of any system, product, or service. It is the composition of factors such as reliability, quality, maintenance, safety, and sustainability [16,27]. These factors are interconnected and collectively contribute to the performability of the plant. When evaluating the performability of a biogas plant, it is crucial to consider the relative relevance of each attribute, recognizing their interdependencies [16]. This is considered in the proposed method by applying the MCDM method. The performability factors are discussed in detail in the following lines.

### 3.1. Quality

The quality of the construction materials used in low-cost biogas plants and the age of the plant impact its performance significantly. Materials with inferior quality will eventually lead to structural damages and seepage issues [28]. In addition to this, the natural disaster and low-quality workmanship will lead to the development of large crack(s) on the walls of outflow and inlet tanks [29]. The quality of construction materials is crucial, even if the design and workmanship are of good quality [30]. The choice of feedstock influences biogas production—for example, feedstock with carbohydrate-rich substrates yields gas with high methane content [31]. Longitudinally designed tubular digesters provide advantages in effectively segregating processing stages and enhancing methane yields during the treatment of high-solid substrates. Moreover, the nutrient content in the digestate, which is used as a fertilizer, determines the quality of the biogas production process.

### 3.2. Reliability

In general, the probability of a system meeting its intended function effectively for the desired operational period of time for electricity generation is defined as reliability. In the context of a biogas plant, reliability can be defined as the likelihood of a biogas plant producing enough biogas for the desired operation period. This means that the plant should produce gas production consistently, without any functional failures. The reliability of a biogas plant is influenced by crucial factors such as the plant's design, construction quality, constituent components' durability, and external elements, including environmental conditions, operational pressures, and the proficiency of operators. The design of the biogas plant plays a crucial role in its reliability, with systems having fewer components connected in series generally exhibiting higher reliability. Out of the four types shown in Figure 3, two-stage biogas plants will have relatively low reliability. Two-stage biogas facilities comprise a sequential arrangement of two digesters. The seamless operation of the entire biogas plant relies on the proper functioning of both digesters. If either of these digesters malfunctions, it will result in the overall failure of the biogas plant.

The corrosive properties of biogas, primarily due to the presence of hydrogen sulfide ($H_2S$), lead to the degradation of vital components such as steel domes, supply pipes, stoves, and internal structures. This corrosion significantly undermines the dependability of the biogas setup. Moreover, the utilization of subpar construction materials increases the likelihood of structural fissures, while inadequate craftsmanship further amplifies the risk of malfunctions. It is imperative to acknowledge that the caliber and dependability of biogas systems are intrinsically linked to these factors. Consequently, we must focus on addressing the corrosive attributes of biogas, utilizing top-notch materials, and ensuring meticulous workmanship [32,33].

### 3.3. Safety

Engineering systems such as biogas plants with a greater risk of accidents can present hazards during their operation and maintenance. Failure of these systems can lead to significant financial costs, safety risks, and environmental impacts. The corrosion of steel structures in biogas plants can result in the leaching of digestate, posing a danger to groundwater. Poor construction materials further increase the risk of methane emissions from various components like pipes, valves, and storage facilities [34]. If a tank breaks down, it can cause a spilling and flood of digestate, which can spread to surrounding areas if not contained promptly. The use of animal and human wastes in anaerobic digestion introduces biological risks due to the presence of harmful bacteria, parasites, and viruses. Moreover, exposure to high concentrations of hydrogen sulfide ($H_2S$) can lead to severe injuries to the human operator. The $H_2S$ does not only affect biogas plant performance but also contributes to the corrosion of steel parts within the system [35].

### 3.4. Maintainability

Insufficient user proficiency in operating and maintaining a biogas plant, as well as performing essential upkeep duties, can result in plant breakdowns and reduced efficiency. Conversely, maintenance serves as a valuable instrument for enhancing the dependability of reparable systems and elevating their performance levels [32]. As an example, practical encounters in two-stage plants have pinpointed the linking conduit between stage I and stage II, along with the stuffing box containing graphite rope, as pivotal elements concerning failure frequency, longevity, and operational as well as upkeep expenses in the realm of renewable energy. Routine assessments, coupled with the implementation of a straightforward soap bubble test to uncover leaks, can proactively avert potential breakdowns. In the case of stationary biogas facilities, the occasional cleaning of the digester and replacement of corroded parts may become essential, especially when using fibrous feedstock. Furthermore, an annual coating of the steel biogas holder with paint is necessary to make it more durable, and replacement may be carried out after 10 years of useful life. Undertaking these maintenance activities is crucial to guarantee the effective operation and prolonged lifespan of the biogas plant. The availability of spares and skilled manpower maintenance of the plant have an impact on its maintainability.

### 3.5. Sustainability

The sustainability of a biogas plant is a crucial factor that depends on several operational characteristics, including the availability of sufficient feedstock to maintain a steady gas supply [36]. Blending biomass with cow dung in the process of co-digestion has been shown to offer greater advantages compared to solo digestion. This practice leads to enhanced process stability, elevated nutritional value, and improved digestibility of the resultant co-digests [37]. Plant operations and maintenance also play a significant role in ensuring the sustainability of biogas plants. Good workmanship during construction is crucial to prevent design flaws that can lead to failures and inefficiencies [38]. The storage of digestate in open tanks can result in the emission of gases like methane and nitrous oxide, ammonia, and odorous substances. To mitigate these emissions, a protective layer covering the liquid's surface can be used. In two-stage digesters, the second stage digester allows for additional digestion and recovery of biogas, minimizing biogas leakage into the atmosphere and increasing overall process efficiency [39]. Apart from this, the biogas plant should not consume excess energy and water for operation as it will contradict the purpose of reducing reliance on fossil fuels, which will undermine its sustainability, in turn affecting the operational cost and plant economies.

It is important to note that performability factors are interrelated. The quality and reliability of the biogas system are closely related. The reliability of biogas gas systems is affected by poor quality or inferior workmanship or component materials. Having a high-quality material used for construction or superior quality of workmanship could result in high reliability. Poor design can prevent a product from being reliable, regardless of its quality. Maintenance is a process of keeping the various units of the biogas system in its operational condition. High maintainability, which facilitates quick and easy servicing, helps maintain the system's reliability. A high-reliability system will have less maintenance work. Keeping a biogas system well-maintained reduces the risk of unexpected failures that can compromise safety. Quality components have a lower failure rate that could jeopardize safety. Breakdown due to safety issues affects the reliability of the biogas system. All dependability factors (i.e., reliability, quality, safety, and maintainability) affect sustainability.

From the discussion presented above, it is evident that the performability factors of biogas are important for operational reliability and sustained business. These ensure consistent performance, reducing downtime and promoting scalability. In competitive industries, these factors provide a crucial edge to any such asset management and ensure compliance. In this proposed work, the selection of the best biogas plant for Indian rural application is carried out with the help of two selected MCDM tools, i.e., AHP and WASPAS, by taking into account the performability factors. The proposed MCDM tools are described in the subsequent section.

## 4. Analytic Hierarchy Process (AHP) and Weighted Aggregated Sum Product Assessment (WASPAS)

Analytic Hierarchy Process (AHP) is a structured approach to decision-making that involves breaking large judgments down into smaller, more manageable ones [40]. The versatile application of AHP spans across diverse sectors, including business, public policy, engineering, and healthcare. AHP facilitates decision-making by allowing decision-makers to consider multiple criteria and perspectives in a structured and methodological manner. Numerous multi-criteria strategies, either alone or in combination, have been employed to support decision-making for sustainable development. However, the technical challenges and optimization of biogas plants using these strategies have not been addressed yet [41]. Among the available MCDM approaches, the AHP is the most commonly used in making decisions [42]. There is an attempt to choose the best biogas upgrading technology using AHP [43], but the selection for rural deployment has never been a point of discussion as there is a lack of data for conducting such a study.

The WASPAS method, which combines the Weighted Product Model (WPM) and Weighted Sum Model (WSM), is one of the most recent MCDM approaches that can improve the ranking accuracy of alternatives. This approach has been proven to be more effective than WSM and WPM [44,45]. This technique has been used for selective decision-making processes and found limited application. There are few research attempts using WASPAS, which focused on the parametric optimization of non-traditional machining processes as well as risk assessment for road projects [45,46]. There are articles that analyzed the performability of natural systems [12].

In the present study, the AHP is employed to evaluate the weights of each performability factor, whereas WASPAS is used for ranking the biogas plants. This hybrid method provides a better alternative optimally.

## 5. Proposed Methodology

In this paper, a framework is proposed to select a small-scale biogas plant based on performability factors using AHP in conjunction with WASPAS. Figure 4 shows the steps involved in the proposed framework.

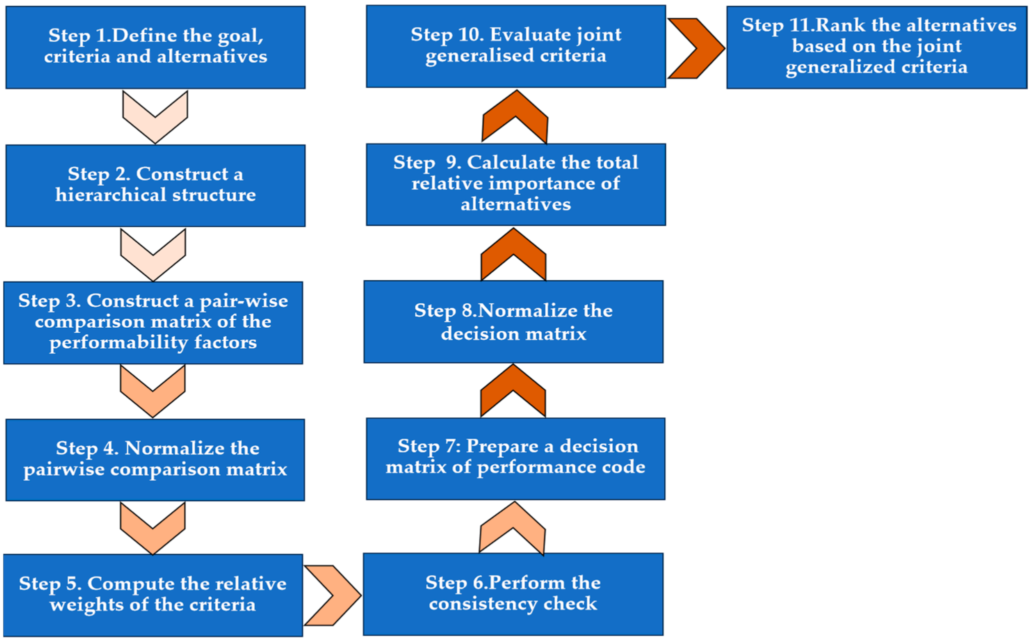


**Figure 4.** Steps involved in the proposed framework.

The weights of the attributes, i.e., the selected performability factors, are determined by the AHP method through a pair-wise comparison of the factors. A consistency check is then performed to measure the results of the comparison. Subsequently, the calculated weights are used in WASPAS to evaluate the total relative importance of the alternatives, i.e., biogas plants, based on the weighted aggregate of the performability factors that helps to determine joint generalized criteria. This is used to rank the alternatives optimally and choose the best biogas plant. The steps of the proposed methodology for selection of the best alternative, i.e., a suitable biogas plant in the context of Indian rural application, are divided into two parts, as outlined in the following lines. Steps 1 to 4 describe AHP, and the rest of the steps illustrate WASPAS [47].

***Step 1*: Define the goal, criteria, and alternatives**

The goal of the proposed work is to choose a suitable biogas plant for the Indian rural application based on performability factors that meet the specific needs of the community and contribute to sustainable development. These factors serve as the criteria for evaluation. The biogas plants—fixed, floating, balloon, and two-stage biogas plants—are among the alternatives taken into consideration.

***Step 2*: Construct a hierarchical structure**

We organize the decision problem, i.e., select the best biogas plant, into a hierarchy by listing the main goal, selection criteria, and decision alternatives at Level I, Level II, and Level III respectively, as represented in Figure 5.

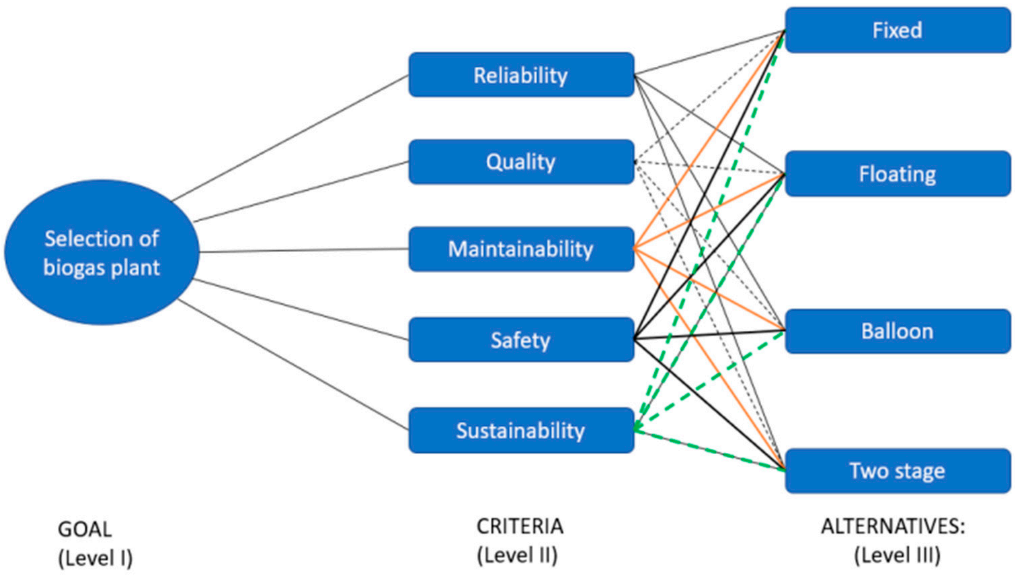


**Figure 5.** A hierarchy structure for the selection of biogas plant problem.

***Step* 3: Construct a pairwise comparison matrix of the performability factors (i.e., Criteria)**

A pairwise comparison matrix (size n × n) is created for the selected criteria, i.e., performability factors, where 'n' is equal to the total number of criteria. The matrix allows for a detailed comparison between the factors based on their importance. A pairwise comparison matrix is developed for a general case and shown in Table 1. The performability factors do differ in terms of degree of importance. Based on this, each factor is assigned a number ranging from 1 (equal importance) to 9 (extreme importance) using the basic AHP scale, as shown in Table 2 [48]. The assignment of this value was carried out by using expert opinions of the design, including those of operational professionals of the biogas plant, researchers, and end users.

**Table 1.** Pair-wise comparison matrix (General case).

| | $\mathbf{B_i}$ | $\mathbf{B_j}$ | . | . | $\mathbf{B_n}$ |
|---|---|---|---|---|---|
| $\mathbf{B_i}$ | 1 | $b_{ij}$ | | | $b_{in}$ |
| $\mathbf{B_j}$ | $1/b_{ij}$ | 1 | | | $b_{jn}$ |
| . | | | | | |
| . | | | | | |
| $\mathbf{B_n}$ | $1/b_{in}$ | $1/b_{jn}$ | | | 1 |

Referring to Table 1, the elements, $\mathbf{B_i}$, $\mathbf{B_j}$, . . ., $\mathbf{B_n}$, and $\mathbf{b_{ij}}$ represent performability factors, **i**, **j**, . . ., **n** and the relative importance of **i**th factor over **j**th factor, respectively.

The experts are the professionals from biogas manufacturing plants, who have reasonable experience in the design, production, installation, and servicing of the biogas plant, the researchers who research the biogas production process, and the end user, who is an expert in the operation and maintenance of the plant. A survey form was designed considering the discussion in Section 3 (Performability Factors) to collect data on the relative importance of performability factors from all these stakeholders. The survey form has a set of questions related to the performability factors and their interrelations.

**Table 2.** AHP scale.

| Definition for Relative Importance | Scale Rating from 1 to 9 |
|---|---|
| Equal importance | 1 |
| Weak | 2 |
| Moderate importance | 3 |
| Moderate plus | 4 |
| Strong importance | 5 |
| Strong plus | 6 |
| Very strong or demonstrated importance | 7 |
| Very, very strong | 8 |
| Extreme importance | 9 |

### *5.1. Sample survey questionnaire for AHP*

In this section of the survey, for each pair of criteria and alternatives, the experts were asked to make a comparative judgment on the importance of a criteria or preference of one over the other. This is typically done using an AHP scale from 1 to 9, where 1 means both are equally important and 9 means one is extremely more important than the other. Meanwhile, if the selected criteria are not extremely important compared to the criteria listed, then the scale rating for that criteria is the reciprocal of 9, i.e., 1/9.

Q1. Rate the importance of the **Quality** over the factors as listed below (Refer to the AHP scale)

A. Reliability [ ]
B. Safety [ ]
C. Maintainability [ ]
D. Sustainability [ ]

Q2. Rate the importance of the **Reliability** over the factors as listed below (Refer to the AHP scale)

A. Safety [ ]
B. Maintainability [ ]
C. Sustainability [ ]
D. Quality (Not required as it is the reciprocal of the rating of Reliability assigned in Q1)

Q3. Rate the importance of the **Safety** over the factors as listed below (Refer to the AHP scale)

A. Maintainability [ ]
B. Sustainability [ ]
C. Quality (Not required as it is the reciprocal of the rating assigned for Safety in Q1)
D. Reliability (Not required as it is the reciprocal of the rating assigned for Safety in Q2)

Q4. Rate the importance of the **Maintainability** over the factor as listed below (Refer to the AHP scale)

A. Sustainability [ ]
B. Quality (Not required as it is the reciprocal of the rating assigned for Maintainability in Q1)
C. Reliability (Not required as it is the reciprocal of the rating assigned for Maintainability in Q2)
D. Safety (Not required as it is the reciprocal of the rating assigned for Maintainability in Q3)

Q5. Rate the importance of the **Sustainability** over the factor as listed below (Refer to the AHP scale)

A. Quality (Not required as it is the reciprocal of the rating assigned for Sustainability in Q1)
B. Reliability (Not required as it is the reciprocal of the rating assigned for Sustainability in Q2)
C. Safety (Not required as it is the reciprocal of the rating assigned for Sustainability in Q3)
D. Maintainability (Not required as it is the reciprocal of the rating assigned for Sustainability in Q4)

By using the rating obtained through the survey using the AHP scale (Table 2) in Table 1, a pair-wise comparison matrix for the performability factors is developed based on the statement, as discussed above and represented in Table 3. Using the survey questionnaires given above, an extensive survey was conducted to collect expert opinions of the design from operational professionals, researchers, and end users in order to assign the relative importance in terms of quantitative value using the AHP scale. For instance, based on the survey, it is observed that the factor reliability has moderate importance compared to the factor quality; hence, value 3 (Refer to Table 2) is assigned as the relative importance of reliability over quality, and the relative importance of quality is rated one-third of reliability by the expert. This means that factor reliability is moderately important compared to factor quality. i.e., it is important to ensure that the biogas plant runs without failures, rather than maintaining quality. It is to be noted that the sampling method used for conducting the survey is the purposive sampling method. Based on this method, the selected participants should have the required expertise and knowledge pertaining to the decision-making criteria and alternatives, which are being considered in the hierarchy. The anticipated number of participants for the present study was 50, with a minimum number of 20 as the sample size required to achieve a marginal error of 19 [49]. There were 44 respondents who participated in the survey. It is worth noting that the AHP can provide better results even if the number of experts participating in the survey is less.

**Table 3.** Pair-wise comparison matrix of the performability factors.

| | **Reliability** | **Quality** | **Maintainability** | **Safety** | **Sustainability** |
|---|---|---|---|---|---|
| **Reliability** | 1 | $b_{12} = 3$ | 3 | 3 | 7 |
| **Quality** | $1/b_{12} = 1/3$ | 1 | 2 | 3 | 3 |
| **Maintainability** | 1/3 | 1/2 | 1 | 2 | 5 |
| **Safety** | 1/3 | 1/3 | 1/2 | 1 | 2 |
| **Sustainability** | 1/7 | 1/3 | 1/5 | 1/2 | 1 |

***Step 4*: Normalize the pairwise comparison matrix**

Normalization helps to identify inconsistencies in the judgments. In order to normalize the matrix, the element in a particular column is divided by the sum of the elements in that respective column using Equation (1) [49]. Similarly, normalization is performed for the entire set of elements.

$$\bar{b}_{ij} = \frac{b_{ij}}{\sum_{i=1}^{n} b_{ij}} \quad (1)$$

For example, let us consider the first column from Table 3. The sum of the elements in the first column is equal to 1 + (1/3) + (1/3) + (1/3) + (1/7), i.e., 2.1429, and using Equation (1), the normalization is carried out as $\frac{1}{2.1429}$, which is equal to 0.4667, as shown in Table 4.

**Table 4.** Normalized matrix with the relative weights.

| | Reliability | Quality | Maintainability | Safety | Sustainability | Relative Weights Vector ($w_j$) |
|---|---|---|---|---|---|---|
| **Reliability** | $\bar{b}_{11} =$ 0.4667 | $\bar{b}_{12} =$ 0.5806 | 0.4478 | 0.3158 | 0.3889 | $w_1 = 0.4400$ |
| **Quality** | 0.1556 | 0.1935 | 0.2985 | 0.3158 | 0.1667 | $w_2 = 0.2260$ |
| **Maintainability** | 0.1556 | 0.0968 | 0.1493 | 0.2105 | 0.2778 | 0.1780 |
| **Safety** | 0.1556 | 0.0645 | 0.0746 | 0.1053 | 0.1111 | 0.1022 |
| **Sustainability** | 0.0667 | 0.0645 | 0.0299 | 0.0526 | 0.0556 | 0.0538 |

***Step 5*: Compute the relative weights of the criteria**

The relative weights represent the importance of the criteria in the decision-making process. Equation (2) is employed to compute the relative weights of the criteria and is presented in Table 4.

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{n} \quad (2)$$

***Step 6*: Perform the consistency check**

The consistency ratio (CR) is used in AHP to assess the consistency of the judgments made by decision-makers. The consistency ratio (CR) is defined as CI/RI, where CI is the consistency index and RI is a random index value derived from a pairwise comparison matrix. The RI value is selected based on the number of criteria used in the problem [49]. Equation (3) is used to calculate the CI.

$$CI = \frac{\lambda_m - n}{n - 1} \quad (3)$$

where $\lambda_m$ is the largest or principal eigenvalue and $n$ is the number of existing items in the matrix.

In order to calculate CI, the comparative pairwise matrix (size n $\times$ n) created in step 3 is multiplied by the relative weight vector (n $\times$ 1) created in step 5. This new vector (size n $\times$ 1) is called the weighted sum value. Each element of the weighted sum value is divided by each element of the relative weight vector to obtain the '$n$' number of eigenvalues. The principal eigenvalue is subsequently calculated by taking an average of all the eigenvalues. AHP allows a CR value up to 0.1 [49]. The CR obtained for the selected biogas plant selection problem is 0.0442, which is less than 0.10. This indicates that the judgment made by the experts through an extensive survey is consistent and reliable.

***Step 7*: Prepare the decision matrix of the performance code (i.e., Employ the WASPAS method)**

The WASPAS method is employed to select the best biogas plant using the calculated relative weights of the criteria. To apply the WASPAS, an evaluation matrix is created by using the formula C = [$c_{ij}$] mxn, where $m$ is the number of alternatives, $n$ is the number of criteria and $x_{ij}$ is the performance of the $i$th alternative with respect to the $j$th criterion. For each alternative, the decision-makers will have to first judge and assign a performance code to each criterion under consideration. The performance code is selected from a 10-point Likert scale, with 1 representing 'Low' and 10 representing 'Exceptionally high' [50]. Based on the survey conducted among biogas plant designers and manufacturers, commissioning and installation agencies in India, researchers, and end users, the performance code is selected for each performability factor corresponding to each alternative, i.e., various types of biogas plant. The sample survey questionnaire for WASPAS is appended below.

### 5.2. Sample Survey Questionnaire for WASPAS

This questionnaire is used to collect the performance code, i.e., the performance rating of each criterion (performability factor) from the interviewees. Under this section, the experts, i.e., interviewees, were asked a set of questions and expected to provide a rating from the Likert scale, which ranges from 1 to 10, indicating 1 as low and 10 as exceptionally high. Multiple responses for a single question shall be averaged.

***Reliability:***

Q1. How would you rate the overall reliability of the four types of biogas plants in terms of consistent gas production?
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q2. Rate the plant in terms of the frequency of failures [ ].
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q3. Based on your knowledge, how do you compare the reliability of each plant in terms of component durability?
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q4. Rate the overall lifespan of the plant [ ].
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].

***Quality:***

Q1. How would you rate the overall build quality of the four types in terms of material durability and construction standards?
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q2. From your experience, rate each type based on the quality of components and longevity.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q3. Rate the methane yield for each type of biogas plant.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q4. Rate the usage of the used slurry as a fertilizer.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].

***Maintainability:***

Q1. How do you rate the
A. Frequency of cleaning of digester tank of these four types of biogas plant.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
B. Frequency of replacement of corroded parts.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
C. Frequency of blockage in feed pipe, outlet, and gas pipe.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q2. From your experience, rate each type of biogas plant for its ease of maintenance.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q3. Rate the availability of the spare parts for the plant.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q4. Rate the availability of skilled manpower.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ]

***Safety:***

Q1. Is there any flooding of digestate on site?
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q2. Is there any spilling of digestate slurry into nearby water bodies?
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q3. Is there uncontrolled emission of biogas?
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q4. Is there any past record of unsafe conditions prevailed?
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].

***Sustainability:***

Q1. From your experience, rate the type of biogas plant based on sustainability in terms of environmental impact, social benefits, and economic viability.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q2. Rate the ease of availability of feed for these types of biogas plants.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q3. From your experience, rate the efficient use of resources such as water and energy for the four types of biogas plants.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].
Q4. Rate the four types of biogas plants based on the overall cost-effectiveness of the biogas plant including capital investment, operational costs, and saving.
Fixed [ ]; Floating [ ]; Balloon [ ]; Two-Stage [ ].

The performance code evaluated based on the survey conducted above is tabulated and presented in Table 5, as given below.

**Table 5.** Performance code for performability factors.

| | Reliability | Quality | Maintainability | Safety | Sustainability |
|---|---|---|---|---|---|
| **Fixed Dome** | 7 | 5 | 3 | 7 | 7 |
| **Floating** | 5 | 6 | 3 | 7 | 5 |
| **Balloon** | 3 | 3 | 2 | 3 | 3 |
| **Two Stage** | 2 | 7 | 2 | 5 | 3 |

*Step 8*: **Normalize the decision matrix**

In the WASPAS method, the factors that affect decision-making are categorized as favorable and unfavorable. All the performability factors are favorable for the selection of types of biogas plants. Hence, normalization by the column of the favorable factors includes dividing each element of the column by the maximum value in that column, as written in Equation (4), which is given below.

$$\bar{c}_{ij} = \frac{c_{ij}}{Max\ (c_{ij})} \tag{4}$$

where $\bar{c}_{ij}$ is the normalized value, $Cij$ is the original value.

The calculated normalized decision matrix is shown in Table 6a,b below.

**Table 6.** (a). Normalized decision matrix. (b). Normalized decision matrix.

**(a)**

| | Reliability | Quality | Maintainability | Safety | Sustainability |
|---|---|---|---|---|---|
| **Fixed Dome** | **7/7** | 5/7 | 3/3 | 7/7 | 7/7 |
| **Floating** | **5/7** | 6/7 | 3/3 | 7/7 | 5/7 |
| **Balloon** | **3/7** | 3/7 | 2/3 | 3/7 | 3/7 |
| **Two Stage** | **2/7** | 7/7 | 2/3 | 5/7 | 3/7 |

**(b)**

| | Reliability | Quality | Maintainability | Safety | Sustainability |
|---|---|---|---|---|---|
| **Fixed Dome** | 1 | 0.7143 | 1 | 1 | 1 |
| **Floating** | 0.7143 | 0.8571 | 1 | 1 | 0.7143 |
| **Balloon** | 0.4286 | 0.4286 | 0.6667 | 0.4286 | 0.4286 |
| **Two Stage** | 0.2857 | 1 | 0.6667 | 0.7143 | 0.4286 |

***Step 9*: Calculate the total relative importance of alternatives based on WSM and WPM**

For calculating the total relative importance of alternatives based on WSM, the relative weight of each performability factor calculated in step 5 is multiplied by the normalized value of the alternative calculated in step 8 (refer to Table 6b), and the resultant is summed up for all factors. Therefore, each criterion's relative importance is reflected in the overall assessment of the alternative, i.e., the selected biogas plant. Mathematically, the total relative importance of *i*th alternative based on WSM is expressed as:

$$Q_i^{(1)} = \sum_{j=1}^{p} \bar{c}_{ij} w_j \tag{5}$$

Here, $\bar{c}_{ij}$ and $w_j$ is the normalized value and the relative weight for each factor from $j$ = 1 to $p$, respectively.

As an example, the calculation of the total relative importance of a fixed dome based on WSM is shown below.

$$Q_{i=1}^{(1)} = \sum_{j=1}^{p=5} \bar{c}_{ij} w_j = 1(0.4400) + 0.7143(0.2260) + 1(0.1780) + 1(0.1022) + 1(0.0538) = 0.9354 \tag{6}$$

Similarly, the total relative importance of the $i$th alternative $Q_i^{(2)}$ using WPM is calculated as the product of the normalized values for each factor raised to the power of their respective weights. Mathematically, it is expressed as Equation (7) below.

$$Q_i^{(2)} = \prod_{j=1}^{n} (\bar{c}_{ij})^{w_j} \tag{7}$$

The sample calculation of the total relative importance of a fixed dome based on WPM is shown below.

$$Q_{i=1}^{(2)} = \prod_{j=1}^{n} (\bar{c}_{ij})^{w_j} = (1)^{0.4400} \times (0.7143)^{0.2260} \times (1)^{0.1780} \times (1)^{0.1022} \times (1)^{0.0538} = 0.9268$$

Table 7 below shows the calculated values of the total relative importance of alternatives based on WSM and WPM.

**Table 7.** Total relative importance of alternatives based on WSM and WPM.

| | $Q_i^{(1)}$ | $Q_i^{(2)}$ |
|---|---|---|
| **Fixed Dome** | 0.9354 | 0.9268 |
| **Floating** | 0.8266 | 0.8179 |
| **Balloon** | 0.4709 | 0.4636 |
| **Two Stage** | 0.5665 | 0.4949 |

***Step 10*: Evaluate joint generalized criteria**

Finally, a joint generalized criterion, represented mathematically as Equation (8), is used to integrate additive and multiplicative operations into a weighted aggregate. It combines components from both the Weighted Sum Model (WSM) and the Weighted Product Model (WPM).

$$Q_i = \lambda Q_i^{(1)} + (1 - \lambda) Q_i^{(2)} \tag{8}$$

The trade-off between the multiplicative and additive components is determined by a value called $\lambda$, which ranges from 0 to 1. It is to be noted that the WASPAS method is changed to WPM when the $\lambda$ is 0, and it becomes the WSM method when $\lambda$ is 1. It has been consistently employed for improving the accuracy of rankings in MCDM problems and potentially achieving the highest estimation accuracy. In order to take equivalent advantage of both WPM and WSM, the value of $\lambda$ is taken as 0.5 for this selection problem. Based on this, the value of joint generalized criteria, i.e., Qs, are evaluated for each alternative, i.e., for each biogas plant, and shown in Table 8 below.

**Table 8.** Joint generalized criteria of alternatives.

| Types of Biogas | Q |
|---|---|
| Fixed Dome | 0.9404 |
| Floating | 0.8026 |
| Balloon | 0.4546 |
| Two Stage | 0.4912 |

***Step 11*: Rank the alternatives based on joint generalized criteria**

The joint generalized criteria (Q) evaluated in the previous step form the basis for ranking the alternatives. The selected biogas plants are ranked based on the value of Qs. The result is presented in the subsequent section.

## 6. Results

The survey conducted for AHP provided quantitative values, which are the input data for developing a pairwise comparison matrix discussed in Section 5. Tables 3 and 4 outline the key stages of the solution process for AHP.

The AHP process creates a set of weights for each criterion, considering their importance in the decision-making process. The criterion-wise relative weights are represented in Figure 6.

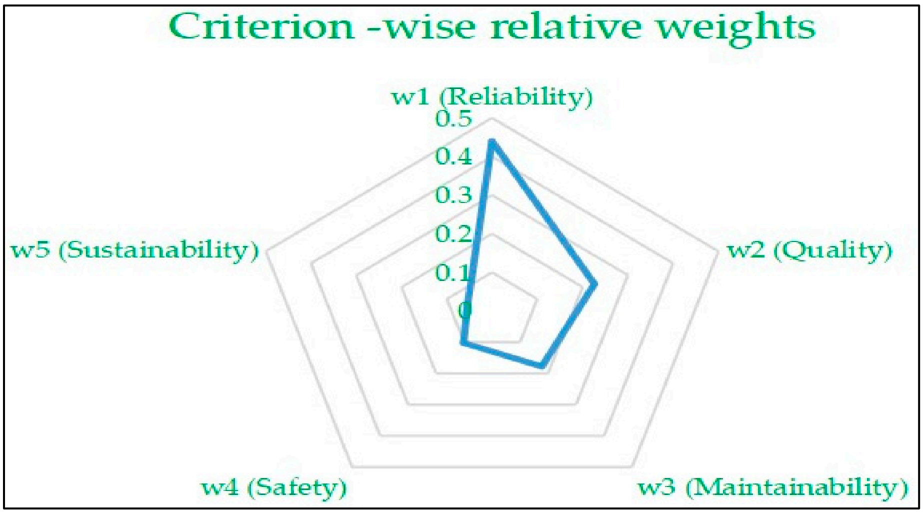


**Figure 6.** Criterion-wise relative weights.

From Figure 6, it is understood that the criterion of reliability has the highest importance, followed by quality, maintainability, safety, and sustainability. The judgment made in the decision-making process is consistent as the CR value for the biogas selection problem is 0.0442, which is less than 0.1 (refer to Step 6). Based on the inputs of experts obtained from the survey, the WASPAS method calculated a score for each alternative (i.e., types of biogas plants) based on their performance on each criterion. WASPAS aggregated these scores to provide a joint generalized criterion of alternatives, taking into account the relative weights assigned to each criterion. Based on this, the value of joint generalized criterion, i.e., Qs, are evaluated, as represented in Table 8. Biogas plants are ranked, with the best option having the highest Q. As represented in Figure 7, the fixed dome is the best biogas plant, followed by floating, balloon, and two-stage biogas plants. Fixed-type biogas plants emerged as the best alternative because they offer the best balance of reliability, quality, maintainability, safety, and sustainability compared to the other biogas plants.

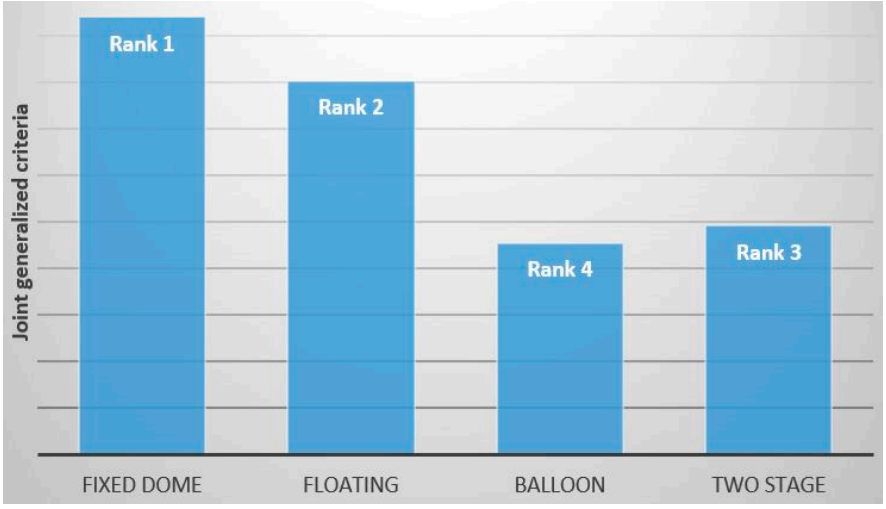


**Figure 7.** Ranking of biogas plants according to Q.

## 7. Discussion

The highest utilization of biogas plants is achieved by sustaining better operational efficiency and optimal performance. The improper selection of the plants will result in various operational issues, which lead to low yield. It is, therefore, essential to select better alternatives among the available biogas plant designs. The crucial selection criteria that are considered for the selection of a better biogas plant are the performability factors, including reliability, quality, maintainability safety, and sustainability. The AHP method was used to evaluate the relative weights of these performability factors by taking into account their relative importance, with reliability scoring the maximum and sustainability the lowest. WAPAS was employed to determine the ranking of biogas plants, with the fixed-dome type securing the highest and the balloon type achieving the lowest. The expert judgment made in the AHP was found to be accepted within consistent limits. The relative weight and performance code of each performability factor of the biogas plants determine the best biogas plant.

***Reliability***: The reliability criteria include not only the failure-free operation of the biogas plant for the uninterrupted supply of biogas but also the long-term costs associated with maintenance, repairs, and operational expenses. The fixed-dome-type biogas plants are less complex with minimal moving parts, hence making them more reliable than other plants.

***Quality***: This criterion evaluates the biogas plant's production rate, construction material, workmanship, quality of components, methane yield, and usage of the slurry as a fertilizer, which determine the quality of the biogas plant. The two-stage biogas plant has a better degree of excellence and provides superior service as compared to other plants, followed by floating. Sustained homogeneous mixing by stirring and more retention time in two-stage plants ensure the production of quality biogas.

***Maintainability***: This criterion considers how easy it is to perform routine maintenance tasks, replace parts, and troubleshoot issues with the biogas plant. The balloon-type model has the advantage of almost maintenance-free operation but has limited operational life. The two-stage plant requires more attention as far as maintenance is concerned as it has additional functional components. The increased number of components brings in more potential points of failure, necessitating more frequent maintenance checks. Repairing balloon-type plants is not viable and thus the scores are poor for maintainability.

***Safety***: The production of biogas, which contains methane, is a risk-prone chemical process if it is not controlled properly. Moreover, poor planned maintenance programs will always keep the plant and surroundings at stake. The better biogas plant design should have minimal or zero safety risk. Fixed- and floating-type plants are better as far as operational safety is concerned, while balloon-type plants are prone to more safety problems, and the gas leakage through the damages of the balloons will be expensive.

***Sustainability***: The sustainability factor is impacted by the availability and quality of feedstock, the maintainability of the plant, pollution, and the energy consumption of the biogas plant. Ballon-type and fixed-type models fare well in maintainability, with reduced pollution and energy consumption. Double-stage reactors not only emit more harmful gases like $N_2S$ but also consume energy for all add-on subsystems, including automated stirring mechanisms. Floating plants do not use energy but release $N_2S$.

Based on the discussion above, fixed-dome-type biogas plants are often favored for their reliability and operational efficiency, meeting specific requirements and environmental considerations based on a careful consideration of all performability factors.

## 8. Conclusions

A framework is presented in this paper for evaluating and selecting the most appropriate type of biogas plant by integrating the Analytic Hierarchy Process (AHP) with Weighted Aggregated Sum Product Assessment (WASPAS). In this method, a holistic evaluation of biogas plant alternatives is ensured by incorporating performability factors such as reliability, quality, safety, maintainability, safety, and sustainability. The relative weights evaluated from the AHP were used in WASPAS to evaluate the factors to help rank the biogas plants. An extensive survey was conducted to collect data from experts for carrying out calculations using AHP and WASPAS to determine the relative weights of the performability factors and joint generalized criteria, respectively. The ranking was performed based on the value of joint generalized criteria (Q). The expert judgment was validated using a consistency check. Based on the analysis, the fixed dome is the most suitable type of biogas plant to be operated in Indian rural areas since it has the highest Q. The proposed method is simple yet more effective in guiding the decision-makers involved in the design and operation of biogas plants in rural India. The method can be employed in situations where there is a scarcity of quantitative data.

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