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Research

Unveiling the hurdles confronting compressed biogas plants: a comprehensive research analysis for sustainable energy solution

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Abstract

The purpose of this work is to identify and analyze the key important barriers to uptake the compressed biogas (CBG) plants in India for enhancing their role as a sustainable energy source. Initially, the barriers are identified from the past academic literature using literature review process and are then validated through the fuzzy Delphi method with expert opinions. The finalized barriers were then categorized into cause effect relationship and ranked for strategic decision making by policy makers, investors, and industry practitioners. We employed the weighted influence non-linear gauge systems (WINGS) method to find hierarchical relationships and determine the priority of these barriers. The findings provide a strategic roadmap for policymakers, investors, and industry stakeholders to enhance CBG adoption through supply chain improvements, financial incentives, public awareness campaigns, and regulatory streamlining. By systematically identifying, linking, and ranking interrelated barriers, the study develops a structured and data-driven framework that provides actionable strategies for accelerating the adoption of compressed biogas (CBG) plants in India.

Article highlights

- Consumer unawareness and poor distribution are major roadblocks to wider adoption of biogas in India.
- Strengthening supply chains and simplifying regulations can speed up biogas plant deployment.
- A strategic approach targeting key barriers can help build a cleaner, more sustainable energy future.

Keywords Supply chain management · Compressed biogas · Sustainability · Energy management

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1 Introduction

Biogas as a substitute for non-renewable energy sources has drawn attention worldwide [21]. Raw Biogas (RB) is not as energy-yield due to, which must be eliminated before using it must be eliminated before using it. These contaminants lead to equipment degradation, fouling, and corrosion in appliances [10]. Therefore, RB must undergo further purification to eliminate contaminants and boost CH_4.

India's energy supply now comes from non-renewable sources, namely coal and oil, which account for about 75% of the country's energy needs. However, only roughly 23.6% of all energy is generated by renewable energy sources, such as small hydro, solar, wind, and [23]. About 45% of the nation's primary energy consumption is currently met by imports, which amounts to roughly 85% of the country's crude oil. This dependence is expected to increase over the next several years. On the other hand, waste organic biomass is widely available in developing nations like India and may even be favored as a feedstock for CBG facilities. Agricultural leftovers (150 MT/year), animal waste (190 MT/year), press mud (20 MT/year), municipal solid waste (MSW) (62 MT/year), and sewage sludge (50 MT/year) are a few of the most widely used feedstocks [4]. Furthermore, a significant amount of trash leftovers is either openly burned or disposed of on the periphery of cities. However, research has shown that open burning of agricultural waste residues occurs in rural regions since storage and transportation are expensive. Although promising, wide-scale adoption of CBG plants in India remains hampered by inefficiencies in supply chains, monetary constraints, regulatory challenges that impede growth, technological issues, and a dearth of consumer education. Previous literature has discussed the technical and economic feasibility concerning the production of CBG, but minimal literature comprehensively identifies and ranks the barriers to its implementation [24]. These barriers and how they interact are essential information for policymakers, investors, and industry stakeholders to develop effective interventions that spur the growth of CBG infrastructure.

Numerous studies have been conducted at the national and international levels to evaluate the part that the Biomass-based energy sector will play in the future energy nexus [3, 13, 15]. Many batch and pilot-size investigations have been conducted in prior research about India to evaluate the potential for RB formation from various organic substrates [20]. There is not much quantitative and qualitative research in the literature regarding the field-scale operational running of the CBG plant in India. Furthermore, none of the studies have addressed the current issues that arise during the setup and efficient operation of CBG plants in the Indian market, such as financial viability, high investment costs, and improper feedstock supply chain management (P et al. 2024). No current research indicates how various barriers relate to and affect each other, so it is challenging to develop integrated policy suggestions [28]. No clear structure is currently in place for ordering and treating barriers to their impact and influence, resulting in piecemeal decision-making [16]. Identifying and prioritizing barriers are necessary because there are interconnecting challenges to be addressed in the CBG adoption process. For example, poor supply chain management can enhance financing risks, and regulatory barriers can potentially deter private capital. Without any systematic framework for analyzing the connectivity between them, addressing barriers singly may result in ineffective solutions.

By identifying contextual interdependencies among barriers, this research allows policymakers and industry players to craft strategies that tackle several issues simultaneously. It is especially crucial in a policy-sensitive sector such as renewable energy, where shifts in one area (financial incentives) may produce ripple effects in others (for instance, technology uptake and grid distribution networks). As a result, there is a research gap about the future of the CBG plant in India, its place in the future energy system, and its ability to reduce future greenhouse gas emissions from India. In light of this, this study responds to the following research questions.

RQ1: What significant barriers affect the compressed biogas plants?
RQ2: How can we establish the contextual linkages between these barriers, and how can we prioritize them strategically?

The following objectives were set to address the above research question: 1. To systematically identify and categorize barriers affecting the adoption of CBG plants in India. 2. To establish interrelationships between these barriers and prioritize them based on their impact. 3. To provide actionable recommendations for policymakers, investors, and industry stakeholders. A literature review was carried out to determine potential barriers. The fuzzy Delphi Method was used to verify the barriers using expert opinions. This is most appropriate in eliciting expert consensus and dealing with the vagueness of qualitative data. A Weighted Influence Non-linear Gauge System (WINGS) methodology was employed to determine interrelationships and rank the barriers according to their influence and importance. The WINGS methodology is warranted since it enables a systematic and quantitative assessment of intricate interdependencies between barriers, guaranteeing that the most important ones are tackled first. This study aims to identify the barriers that CBG plants face in the Indian setting, highlighting important roadblocks that prevent this technology from being integrated smoothly. The challenges are many and complex, ranging from deficiencies in the feedstock supply chain management process to the extensive regulatory environment, permissions, and different frameworks.

The remainder of this paper is structured as follows: Sect. 2 details the literature review. Sections 3 and 4 discuss the methodology and steps for fuzzy Delphi and WINGS. Section 5 presents a detailed discussion of the results, highlighting the significant barriers identified and their prioritization. Section 6 discusses the implications derived from the findings, and Sect. 7 gives the conclusion and limitations of the study.

2 Literature review

Biogas technology has shown promise as a means of achieving sustainable development, boosting energy security, and reducing environmental risks at the same time [30]. The production and use of biogas lowers greenhouse gas emissions and the need for fossil or solid fuels. When used as a biofertilizer, the digestate of biogas can replace artificial fertilizer in the soil. However, the concentration of animal farming and the waning interest in home biogas present new chances for the commercialization of biogas technology. In recent years, there has been a shift in the worldwide biogas industry towards increased industrialization and commercialization. Growing global awareness and the adoption of pertinent laws and regulations in several nations have aided in this advancement [31]. However, there are common issues that large-scale biogas facilities in all nations must deal with, most of which are caused by process instability [32].

Biogas facilities need a substantial upfront investment that needs to be justified, and their continued functioning depends on expensive, attentive maintenance, which must be paid for with money from gas and biofertilizer sales. In light of these financial realities, stakeholders in biogas plants need to take additional regulatory framework requirements and potential incentives into consideration [25]. Poor feedstock supply management has been a significant problem for most CBG operations in India. However, for CBG plant owners, major insufficient financial assistance (subsidiary schemes, government subsidies, and private investors) has been a significant obstacle. Establishing a CBG facility necessitates obtaining numerous regulatory regulations, clearances, and permits from various government bodies. The intricate regulatory framework presents notable obstacles for investors, project developers, and technology vendors seeking to participate in the CBG industry within India. Although there are not many long-term users of CBG, it is a clean fuel substitute that is still in its infancy [33].

This study focuses on identifying the barriers linkages to finding the linkages and prioritizing them. The Weighted Influence Non-linear Gauge System (WINGS) method prioritizes contextual relationships between identified barriers to address the research question. The barriers were identified from the past academic literature shown in (Table 1) and confirmed with the Fuzzy Delphi study. We conducted a comprehensive search using the Scopus and Web of Science databases. The search was limited to peer-reviewed journal articles published in English, while excluding books, book chapters, and conference proceedings. We used the following keywords for our search: "compressed biogas," "energy," "supply chain," and "sustainability." This initial search yielded a total of 84 articles. After a thorough screening of the abstracts for relevance to the study's objectives, 57 articles were finalized for detailed review and analysis to identify the list of barriers.

3 Methodology

3.1 Research design

To prepare a multilevel structural model, we have identified the barriers and strive to devise a strategy to overcome them. A comprehensive literature review can quickly determine the following properties of the system methodology comprehensive literature review, Fuzzy Delphi Method, and WINGS methodology can quickly determine following properties of the system. 1. Interpretative—In this process, the relationships between the barriers are taken from the group of experts. 2. Structuralism—We evaluated the relationship extracted from the variables in this process. 3. Modelling technique- The outcome is configured by relationships between elements and extracted structure. The

Table 1 List of barriers affecting CBG plants

Sr. No.	Barriers	Description	References
B1	Inadequate supply chain management	Inadequate logistics and infrastructure cause feedstock collection, storage, and delivery to become unproductive to a plant. Focuses on feedstock collection, storage inefficiencies, and transportation delays	[11]
B2	Financial hurdles	High start-up costs for an investment in any CBG project and poor availability of subsidies and private finance make a project financially infeasible to various stakeholders	[2, 12]
B3	Lack of bioconversion technologies	There are limited advancements in efficient biogas upgrading technologies, which further limits the quality and yield of CBG production	[14, 17]
B4	Low consumer awareness about CBG and its by-products	Inadequate public awareness about the benefits and applications of CBG leads to low market demand and adoption rates	[1, 10]
B5	Multiple governmental regulations	This barrier indicates the absence of a single and streamlined regulatory framework that controls CBG operations. Practically, developers are bogged down with long delays and uncertainty due to duplicative requirements from several agencies (e.g., Ministry of Environment, Ministry of Petroleum, State Pollution Control Boards). For example, divergent implementation of the SATAT (Sustainable Alternative Towards Affordable Transportation) scheme by states causes uncertainty in incentives and approvals, deterring new entrants	[8, 18]
B6	Limited knowledge amongst supplier/farmers	Farmers and suppliers lack technical knowledge on feedstock processing and biogas generation, which hampers efficient production	[6, 27]
B7	Immature distribution network of current CBGs	Poor infrastructure for transportation and supply of CBG to end-users hinders market growth and operational viability	[34]
B8	Lack of interest by policymakers	This barrier reflects the lack of explicit, long-term government support required to take the CBG industry to scale. It encompasses weak fiscal incentives, such as a lack of guaranteed procurement arrangements (e.g., no long-term purchase commitments by oil marketing companies) and slow policy implementation. A case in point is the lateness with which waste segregation regulations directly impacting the availability of clean feedstock to CBG facilities have been implemented, thus lowering their efficiency and investor confidence	[7]

Fuzzy Delphi Method has been used for the validation of barriers with input from experts, as this particular method is used to capture expert consensus and handle uncertainties associated with the qualitative data; it is comparatively better than traditional Delphi in a decision-making manner because it integrates opinion from experts with some degree of confidence, which could reduce bias and subjectivity [9]. WINGS was utilized to determine interrelationships and rank the barriers in terms of influence and importance. In contrast to traditional ranking techniques, such as AHP or DEMATEL, WINGS is beneficial because it considers non-linear interdependencies among barriers to provide an overall understanding of interdependencies [26]. Therefore, the most impactful barriers will be addressed first to maximize strategic benefits. In order to ensure the strength of our conclusions, we utilized a formalized data-gathering strategy for both Fuzzy Delphi and WINGS. The information was gathered using expert consultations, surveys, and semi-structured interviews with relevant CBG sector stakeholders. A total of 15 experts were chosen to participate based on their qualifications and years of experience in renewable energy and biogas technology,they include researchers, policymakers, industry practitioners, and supply chain managers. Expert Profiles are given in (Table A1 in Appendix. The previous study suggests the requirement of 10–18 experts on the Delphi panel [5]. The Fuzzy Delphi method was used to fine-tune and validate the identified barriers with iteration of expert feedback toward obtaining consensus and reliability in the results.

The WINGS method was then applied to establish the interrelationships and prioritization of barriers. The input for this analysis was derived from expert responses, which were quantified and weighted based on their perceived influence. The detailed step-by-step methodology followed is shown in Fig. 1.

3.2 Comprehensive literature review and stakeholder discussions

A comprehensive literature review and expert interviews are adopted to identify barriers to adopting CBG plants in India. The Barrier selection process involves an extensive literature survey and face-to-face interviews with the stakeholders/experts in academia and in-field practitioners in the production and business operations of CBG. A field study of CBG plants across varied districts in central India is done to visit the farmers, CBG stakeholders, CBG experts, etc. The literature study illustrates the heterogeneity of barriers, which aims to use expert panels to achieve consensus (Moeuf et al. 2020).

3.3 Fuzzy Delphi method (FDM)

The Delphi method is a successful tool for qualitative research to identify and prioritize managerial decisions (Pawlowski 2004). The previous study suggests that the requirement of 10–18 experts on the Delphi panel is sufficient for this analysis [5]. Fifteen experts from academics, practitioners, and industry domains were selected to be part of the research. These experts work in Compressed biogas as researchers, farmers, aggregators, and government or non-government organization (NGO) employees.

Application of Fuzzy Delphi Method:

Step 1. Experts are invited to analyze performance metrics according to the importance and weight of performance metrics using variables.

Step 2. Tale A2 in the Appendix referred from (Ahmad Zamzuri et al. 2022) shows the conversion of variables in triangular fuzzy numbers.

Step 3. Calculating the distance between average and expert evaluation data of fuzzy numbers for each performance metric. If $\widetilde{m}, \widetilde{n}$ If there are two fuzzy numbers, then the distance between two fuzzy numbers is $d\left(\widetilde{m}\widetilde{n}\right) foundfrom$ Eq (1)

$$d\left(\widetilde{m}\widetilde{n}\right) = \sqrt{\frac{1}{k}\left[\left(m_1 - n_1\right)^2 + \left(m_2 - n_2\right)^2 + \left(m_3 - n_3\right)^2\right]}. \tag{1}$$

Step 4. Aggregate fuzzy evaluation of the performance metric calculated by Eq. (2)

$$Fuzzyevaluation_i = \frac{1}{3}\sum_{1}^{k}(m_{i1}^k + m_{i2}^k + m_{i3}^k). \tag{2}$$

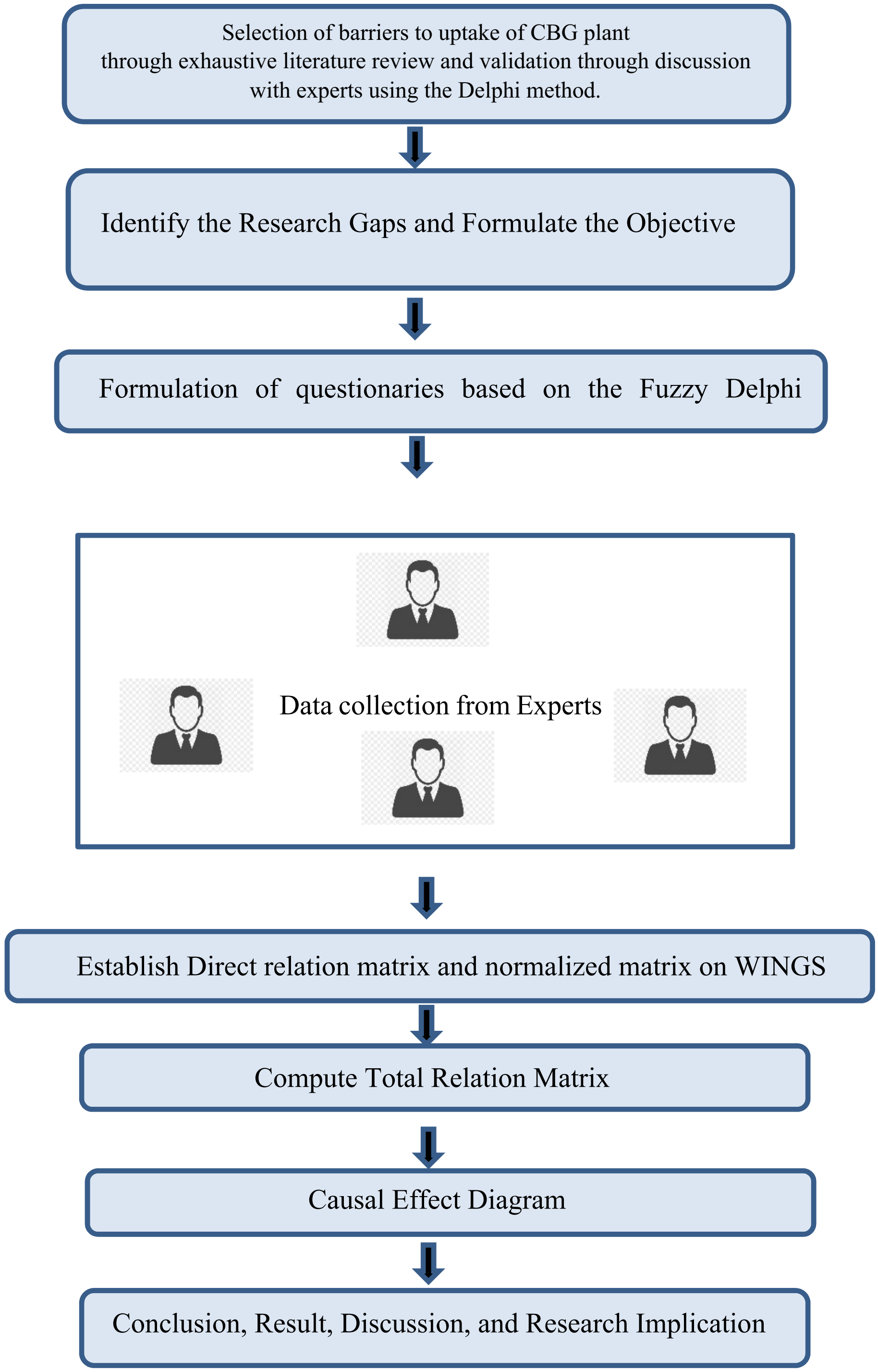

Fig. 1 Research methodology flowchart

If the distance between the average and the expert's evaluation data is ≤ 0.2, then all experts are said to have a consensus. If the percentage of achieving group consensus is more significant than 70%, then it is said to have group consensus and no need for a second round (Mohamad et al. 2015).

3.4 N-WINGS method

The N-WINGS method is employed to consider the individual strength of the Compressed Bio-Gas (CBG) barriers in group decision-making. N-WINGS approach identifies the important CBG Barriers and the degree of influence relationships between the barriers. Then the interpretative structural modeling approach is integrated into the

N-WINGS method to understand the hierarchical model to overcome barriers in CBG. This method identifies an Influence relation map and a directed graph to devise a strategy.

Step 1. A set of experts evaluates the influential relationship between two CBG Barriers. This step collects the influence of CBG barrier i over j in the semantic symbols N, VL, L, H, and VH. The individual strength of the CBG barrier and its intensity are also analyzed in this step according to semantic expressions discussed earlier. This article utilizes the Neutrosophic Number Theory and its Triangular Neutrosophic number (TNNs) set to evaluate inter-barrier influence and self-intensity of barriers (Table A3 Appendix).
Step 2. The interrelationship of CBG Barriers is collected using Neutrosophic sets in a direct strength influence matrix. i.e.,*MbyEquation*3. The single-valued Neutrosophic numbers (e.g., $\langle(a1, a2, a3);\alpha_{\tilde{a}}, \theta_{\tilde{a}}, \beta_{\tilde{a}}\rangle$) constitute the direct strength-influence matrix of CBG Barriers (Table A4 Appendix).

$$D = \begin{bmatrix} \langle(a1, a2, a3);\alpha_a, \theta_a, \beta_a\rangle_{11} & \langle(a1, a2, a3);\alpha_a, \theta_a, \beta_a\rangle_{12} & \dots & \langle(a1, a2, a3);\alpha_a, \theta_a, \beta_a\rangle_{1n} \\ \vdots & \ddots & \ddots & \vdots \\ \langle(a1, a2, a3);\alpha_a, \theta_a, \beta_a\rangle_{n1} & \langle(a1, a2, a3);\alpha_a, \theta_a, \beta_a\rangle_{n2} & \dots & \langle(a1, a2, a3);\alpha_a, \theta_a, \beta_a\rangle_{nn} \end{bmatrix} \tag{3}$$

Step 3. The score function $S(a)$ is employed to convert the Neutrosophic direct strength relation matrix D_{ij} into crisp value matrix CV_{ij} using crisp value formulae.

$$S(a_{ij}) = \frac{1}{8} * (a1 + a2 + a3) * (2 + \alpha_{\tilde{a}} - \theta_{\tilde{a}} - \beta_{\tilde{a}}),$$

where $i, j = 1 toanumberoffactors$.

$$CV_{ij} = S(a_{ij}).$$

The expert opinion crisp value matrix is combined further to create a mean crisp value matrix using geometric mean. The geometric mean maintains the variability of relationships while combining all expert matrices [35].
Step 5. Normalizing a crisp, direct strength-influence matrix CV.

$$N = CV_{ij}/s,$$

$$s = \max\left(\max_{1 \le i \le n} \sum_{j=1}^{n} CV_{ij}, \max_{1 \le i \le n} \sum_{i=1}^{n} CV_{ij} \right).$$

Step 6. The total strength-influence matrix T and Prominence-relation map

$$T = t_{ij} = N(I - N)^{-1}$$

$$W = [r_i]_{nx1} = \lceil \sum_{j=1}^{n} t_{ij} \rceil_{nx1} ;i.e.Sumofrows.$$

$$V = [c_j]_{1xn} = \left[\sum_{i=1}^{n} t_{ij} \right]_{1xm}^{T} i.e.Sumofcolumns.$$

The horizontal axis vector (W + V): = prominence (i.e., strength and influence given and received of the barrier), and the vertical axis vector (W–V): = relation (i.e., the net effect that barrier contributes to the system). If $(w_j - v_j)$ is positive, then the barrier F_j has a net influence on other barriers and can be grouped into cause groups. If $(w_j - v_j)$ is negative, then the barrier F_j is influenced by other barriers and should be grouped into effect groups.

Table 2 Total interaction matrix

Code	Barriers	Weights	Rank	Promina	Relation	Group
B1	Inadequate supply chain management	0.1437	1	11.8565	0.0215	Cause
B2	Financial hurdles	0.114	6	9.4079	– 0.8402	Effect
B3	Lack of bioconversion technologies	0.1183	5	9.7627	0.5467	Cause
B4	Low consumer awareness about CBG and its byproducts	0.139	3	11.4731	1.2251	Cause
B5	Multiple governmental regulations	0.1042	7	8.6007	– 0.8912	Effect
B6	Limited knowledge amongst supplier/farmers	0.1345	4	11.0973	– 0.0327	Effect
B7	Immature distribution network of current CBGs	0.1427	2	11.7762	0.7626	Cause
B8	Lack of interest by policymakers	0.1036	8	8.5522	– 0.7919	Effect

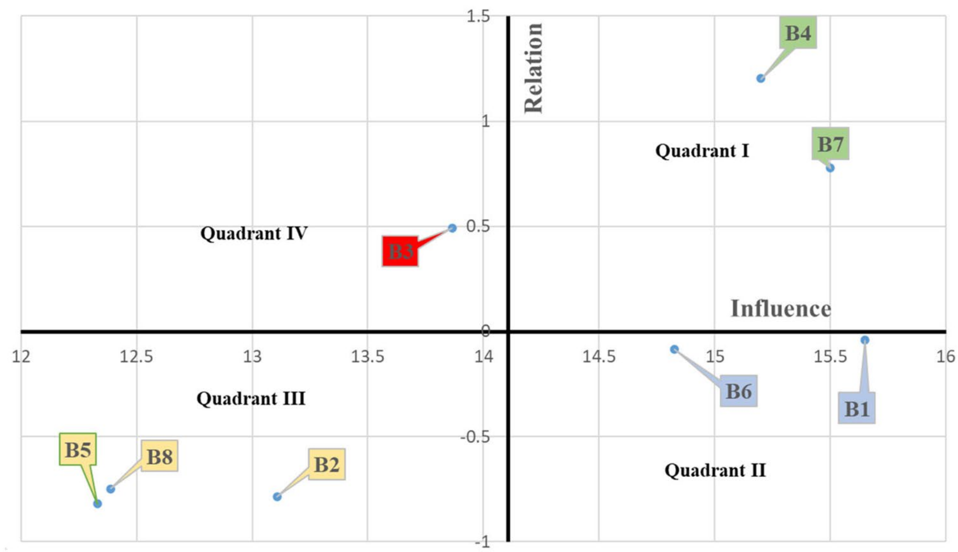

Fig. 2 Influence relation map and quadrant layout

4 Results

The research article analyzes the challenges in the adaptation of CBG plants in India as a sustainable energy solution with an intense literature review and the N-WINGS method. The neutrosophic numbers theory is adopted to tackle subjectivity and uncertainty in the expert opinion. The total interaction matrix is calculated from the interrelationship matrix, which is shown in Table 2.

The Influence relation map is depicted in Fig. 1. The quadrant I and IV contains influential (cause) barriers. B3 (Lack of Bioconversion Technologies), B4 (Low Consumer awareness about CBG and its by-products), and B7 (Immature Distribution Network of current CBGs) are the causal barriers. Barriers in quadrant I (B4, B7) are highly influential barriers in the system. It also possesses high relation. These are the most important barriers. B7 stays in quadrant IV, signifying its importance but can be overcome by other barriers. Quadrant II and III groups affect barriers in the system. Quadrant II assembles barriers B1 (Inadequate Supply Chain Management) and B6 (Limited knowledge amongst Suppliers/Farmers). These are important barriers that can be improved by using other cause barriers. Quadrant III contains B2 (Financial Hurdles), B5 (Multiple Governmental Regulations), and B8 (Lack of Interest by Policymakers). These are not important barriers to the system as they possess low influence and low relation value. The digraph depicted in Fig. 2 has a starting point B4, which is directly impacting all other barriers. It has a high causal influence on the system. After that, B3 is impacting other barriers. The third level is occupied by B7. B1 is at the fourth stage. Thereafter B6, B2, and B5, respectively. B8 stays at the end of the influence diagram. The results obtained are consistent with the research [22]. The CBG plant should consider the implementation of efficient strategies for managing the supply chain. These strategies may include the establishment of partnerships with dependable suppliers of feedstock, the optimization of processes related to the storage and handling of feedstock, and the adoption of monitoring and control systems that effectively ensure the quality and consistency of the feedstock.

5 Discussion

Results from this research outline the main hindrances to the mass adoption of CBG plants in India that mirror findings based on previous studies concerning renewable energy transitions. Unlike previous literature, financial difficulties, regulatory complexity, and lack of efficiency along supply chains lead to the strongest barrier to adoption for CBG plants. While establishing a structured priority for these barriers, this research demonstrates that, on average, low consumer awareness and an immature distribution network remain the highest casual influences on the system. All these findings reflect the need to develop a multidimensional approach aimed at policy reform, technological breakthroughs, and stakeholder mobilization to unlock the growth opportunities of CBG plants. The study also focuses on the interconnectivity of these barriers, which confirms that addressing a single obstacle in isolation is not enough. Instead, a strategic, integrated approach is required to overcome these systemic challenges and enable a sustainable CBG ecosystem in India. To make the study practically applicable, several strategies can be proposed to mitigate the identified barriers. It is important for supply chain management to be reinforced through investment in infrastructure, the use of digital tracking systems, and capacity-building programs for farmers and suppliers. It is possible to mitigate financial constraints through targeted subsidies from the government, low-interest financing schemes, and incentives provided for public–private partnerships. To overcome the regulatory hurdles, policymakers need to simplify the approval process, define clear rules, and develop a single-window regulatory authority for CBG projects. Consumer awareness can be promoted through nationwide campaigns, educational programs, and incentive-based adoption policies that can raise demand for CBG products. Bioconversion technology should be promoted through research grants, industry collaboration, and knowledge sharing with world leaders in biogas technology [24]. By implementing these strategies, India can create a very supportive environment for the large-scale adoption of CBG towards sustainability and long-term viability. Figure 3 shows the hierarchical influence structure that was developed employing the Weighted Influence Non-linear Gauge System (WINGS) approach. It illustrates how the barriers to the adoption of Compressed Biogas (CBG) that were found to be related to each other are connected, highlighting which of them have the most important cascading impacts on the system. The figure is arranged in several levels, where higher-level barriers show greater influence on lower-level ones.

For example, "low consumer awareness" and "immature distribution network" come at the top of the hierarchy, which suggests that these are the factors with a large degree of influence on other barriers like financial limitations, inefficiency in the supply chain, and policy loopholes. This hierarchical design enables stakeholders to pinpoint the most influential barriers to overcome first, thus ensuring the most optimal utilization of intervention measures. The figure thus serves to graphically represent the systemic nature of the issues and to justify the strategic prioritization suggested in the study. The results of this study are primarily consistent with prior research emphasizing the role of financial, regulatory,

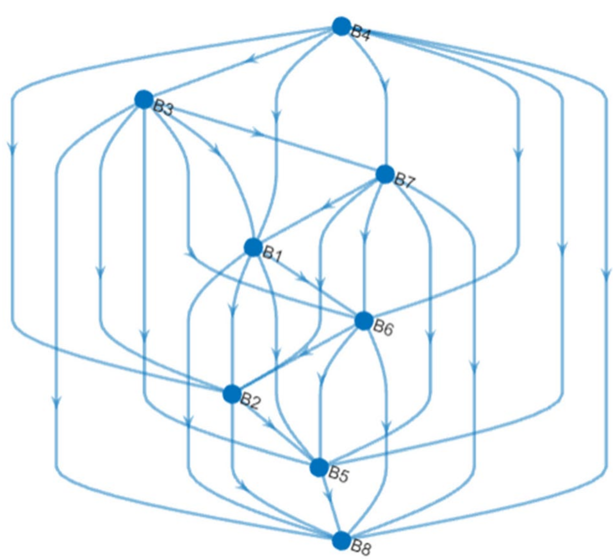

Fig. 3 Hierarchical influence diagram of barriers to CBG adoption

and awareness-related issues in the adoption of renewable technologies. For example, research by Mittal et al. [19] and Singh and Kalamdhad [23] also reported regulatory complexity and consumer unawareness as significant barriers to the deployment of biogas plants in India. Our research develops these insights by not only re-affirming these barriers but also characterizing their hierarchical impacts and interdependencies through the WINGS approach.

Nonetheless, in contrast to prior research centered predominantly around either technical feasibility or individual stakeholder views, our research combines expert-led validation and systemic prioritization. In addition, whereas (Mukeshimana et al. 2021) highlighted capital cost as the overarching barrier, our findings indicate that upstream factors like consumer awareness and distribution infrastructure have even more significant influence, which in turn indirectly magnifies financial and technological issues. This disparity can be explained by our approach's capacity to identify non-linear influence routes through multiple barriers. These comparative insights not only validate the robustness of our findings but also emphasize the need for a systems-thinking perspective when designing efficient CBG promotion strategy to suit the Indian context.

The effect group ranking used here is derived from the cumulative influence scores computed by the WINGS method, which measures the extent to which each barrier influences or is influenced by others in the system. Higher total outgoing influence scores were placed in the "cause group," and higher incoming influence was placed in the "effect group." The validation was done by presenting the initial effect group rankings to a panel of 15 domain experts, ranging from policymakers and academicians to industry practitioners. They evaluated the rankings from their experience and contextual knowledge about the CBG ecosystem in India, and their inputs were taken in order to enhance and validate the final classification.

On validation, the ranking demonstrates that obstacles such as low levels of knowledge on the part of suppliers and insufficient policy support are mainly reactive and symptomatic of upstream problems like supply chain inefficiencies and poor consumer awareness. This categorization was cross-checked with expert judgment to ensure congruence with actual-world interdependencies. The aim of this ranking is to enable stakeholders to differentiate between root-cause barriers that need urgent strategic focus and effect-driven barriers that can be addressed once primary drivers are tackled. This distinction enhances the pragmatic value of the prioritization framework for informing policy and investment choices in the CBG industry.

6 Implications

This study makes a contribution to the academic debate by providing a structured framework in which barriers to the adoption of CBG could be identified and prioritized. By using state-of-the-art methodologies such as the Fuzzy Delphi Method and the Weighted Influence Non-linear Gauge System (WINGS), the study expands the extant literature related to renewable energy barriers and interdependencies. This study bridges the gap between qualitative and quantitative analysis by integrating expert opinions with empirical findings, providing a replicable model for future studies on sustainable energy adoption. It also sophisticates the theoretical understanding of supply chain complexities, regulatory challenges, and technological limitations in the biogas sector. Moreover, the research introduces a new approach for assessing nonlinear relationships among barriers, thereby strengthening methodological contributions to energy transition studies.

This research contributes to the academic debate by providing a structured framework to identify and rank barriers to CBG adoption. Using advanced methodologies, such as the Fuzzy Delphi Method and the Weighted Influence Nonlinear Gauge System (WINGS), the study expands on current literature regarding the interdependencies of renewable energy barriers. This research bridges the gap between qualitative and quantitative analysis through the integration of expert opinions and empirical findings to provide a replicable model for future studies on sustainable energy adoption.

For industry practitioners, this research gives actionable insights on how to overcome key operational challenges associated with CBG adoption. Supply chain inefficiencies and financial constraints can be mitigated through strategic partnerships and targeted investments in infrastructure. Further, businesses can use the prioritization framework to address the most critical barriers first, thereby optimizing resources and enhancing the feasibility of large-scale CBG implementation. Policymakers can use such knowledge to design efficient regulatory structures and launch incentive schemes to increase investor confidence. The research study also places emphasis on capacity building in order to raise the stakeholder's awareness about biogas technologies and the financial benefits they bring to them. In addition, corporate decision-makers can develop adaptive strategies to incorporate sustainable practices into well-functioning energy supply chains to ensure sustainability and market strength for a long time.

7 Conclusion

This research rigorously determines and ranks the obstacles to Compressed Biogas (CBG) plant adoption in India. The major issues like poor supply chain management, financial limitations, regulatory issues, and technology constraints were underscored. Utilizing the Fuzzy Delphi Method and Weighted Influence Non-linear Gauge System (WINGS), the research determines interdependence among these obstacles, providing a strategic guide toward directed policy action and industry reforms.

One of the primary contributions of this study is that it has a structured prioritization framework that directs policymakers, practitioners in the industry, and investors to address the most impactful impediments first. Enhancing supply chain networks, enacting encouraging government policies, raising financial rewards, and embracing technological innovations are essential measures for driving CBG adoption. Apart from its contribution, the study has some limitations. Relying on experts' views might imply subjectivity, and focusing on India might restrict the direct applicability of results to other parts of the world. Future studies would incorporate empirical evidence from case studies, surveys, and cross-country analysis to improve the generalizability and applicability of the outcomes. Further, a search for new policy mechanisms and technologies will also advance global development in terms of sustainable bioenergy solutions.

In addition, as the world energy landscape continues to change, the incorporation of digital technologies like blockchain for supply chain visibility and artificial intelligence for process improvement could make CBG operations more efficient. Governments, industries, and research institutions will have to work together to scale up CBG infrastructure and make it sustainable in the long term as an energy source. Overcoming the set barriers with the involvement of multi-stakeholders and policy-making based on evidence will be instrumental in realizing the full potential of CBG to deliver energy security and environmental sustainability.

8 Limitation and future scope

Despite the contributions made, this study has some limitations. First, it relies on expert opinions when conducting the study. This introduces a subjective process for the identification and prioritization of barriers. Secondly, this study uses a structured prioritization method, yet in real-life practice, things might not fit as well in the model that has been structured. Lastly, this study focused on India. Without further adaptation, findings are not directly applicable to other geographic locations. Further studies may analyze dynamic change over time, including the impact that policy reforms, technological changes, and market dynamics may trigger in the adoption of CBG. More evidence can also be generated by including a cross-country comparative analysis to study differences in regulatory and economic environments in countries. Finally, using real-world data and case studies, empirical research would serve to validate the framework for prioritization and further develop its applicability in many different contexts. Examining the role of digital technologies like blockchain and AI in optimizing the supply chain of CBG can be another interesting avenue for further exploration.

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Data availability The datasets generated and/or analysed during the current study are available from the authors on reasonable request.

Declarations

Ethics approval and consent to participate This study was approved by the Ethics Committee of the Indian Institute of Management -Sambalpur, India. The research was conducted in accordance with the institution's ethical guidelines.

Informed consent Informed consent was obtained from all participants involved in the study. No participants were below the age of 18 years. Consents to participate and to publish was documented for each participant.

Competing interests The authors declare no competing interests.

References

1. Ali S, Yan Q, Irfan M, Chen Z. Evaluating barriers to biogas technology adoption in China: the moderating role of awareness and technology understanding. Front Environ Sci. 2022. https://doi.org/10.3389/fenvs.2022.887084.
2. Baena-Moreno F, González-Castaño M, Arellano-Garcia H, Reina T. Exploring profitability of bioeconomy paths: dimethyl ether from biogas as a case study. Energy. 2021;225: 120230. https://doi.org/10.1016/J.ENERGY.2021.120230.
3. Batidzirai B, Smeets EMW, Faaij APC. Harmonizing bioenergy resource potentials—methodological lessons from a review of the state-of-the-art bioenergy potential assessments. Renewable Sustain Energy Rev. 2012;16(9):6598–630. https://doi.org/10.1016/j.rser.2012.09.002.
4. Chavan D, Lakshmikanthan P, Manjunatha GS, Singh D, Khati S, Arya S, Tardio J, Eshtiaghi N, Mandal P, Kumar S, Kumar R. Determination of risk of spontaneous waste ignition and leachate quality for open municipal solid waste dumpsite. Waste Manage. 2022;154:272–82. https://doi.org/10.1016/j.wasman.2022.10.008.
5. Culot G, Orzes G, Sartor M, Nassimbeni G. The future of manufacturing: a Delphi-based scenario analysis on Industry 4.0. Technol Forecast Soc Change. 2020;157: 120092. https://doi.org/10.1016/j.techfore.2020.120092.
6. Czubaszek R, Wysocka-Czubaszek A, Banaszuk P. Importance of feedstock in a small-scale agricultural biogas plant. Energies. 2022. https://doi.org/10.3390/en15207749.
7. Dahlgren S. Biogas-based fuels as renewable energy in the transport sector: an overview of the potential of using CBG, LBG and other vehicle fuels produced from biogas. Biofuels. 2020;13:587–99. https://doi.org/10.1080/17597269.2020.1821571.
8. Goulding D, Fitzpatrick D, O'Connor R, Browne J, Power N. Supplying bio-compressed natural gas to the transport industry in Ireland: is the current regulatory framework facilitating or hindering development? Energy. 2017;136:80–9. https://doi.org/10.1016/J.ENERGY.2016.08.037.
9. Hsu YL, Lee CH, Kreng VB. The application of Fuzzy Delphi Method and Fuzzy AHP in lubricant regenerative technology selection. Expert Syst Appl. 2010;37(1):419–25. https://doi.org/10.1016/j.eswa.2009.05.068.
10. Khan I, Othman M, Hashim H, Matsuura T, Ismail A, Rezaei-DashtArzhandi M, Azelee I. Biogas as a renewable energy fuel—a review of biogas upgrading, utilisation and storage. Energy Convers Manage. 2017;150:277–94. https://doi.org/10.1016/J.ENCONMAN.2017.08.035.
11. Ko S, Lautala P, Handler R. Securing the feedstock procurement for bioenergy products: a literature review on the biomass transportation and logistics. J Clean Prod. 2018. https://doi.org/10.1016/J.JCLEPRO.2018.07.241.
12. Kusz D, Kusz B, Wicki L, Nowakowski T, Kata R, Brejta W, Kasprzyk A, Barć M. The economic efficiencies of investment in biogas plants—a case study of a biogas plant using waste from a dairy farm in Poland. Energies. 2024. https://doi.org/10.3390/en17153760.
13. Meyer AKP, Ehimen EA, Holm-Nielsen JB. Future European biogas: animal manure, straw and grass potentials for a sustainable European biogas production. Biomass Bioenergy. 2018;111:154–64. https://doi.org/10.1016/j.biombioe.2017.05.013.
14. Miltner M, Makaruk A, Harasek M. Review on available biogas upgrading technologies and innovations towards advanced solutions. J Clean Prod. 2017;161:1329–37. https://doi.org/10.1016/J.JCLEPRO.2017.06.045.
15. Mittal S, Ahlgren EO, Shukla PR. Future biogas resource potential in India: a bottom-up analysis. Renewable Energy. 2019;141:379–89. https://doi.org/10.1016/j.renene.2019.03.133.
16. Nevzorova T, Kutcherov V. Barriers to the wider implementation of biogas as a source of energy: a state-of-the-art review. Energy Strat Rev. 2019. https://doi.org/10.1016/j.esr.2019.100414.
17. Nguyen L, Kumar J, Vu M, Mohammed J, Pathak N, Commault A, Sutherland D, Zdarta J, Tyagi V, Nghiem L. Biomethane production from anaerobic co-digestion at wastewater treatment plants: a critical review on development and innovations in biogas upgrading techniques. Sci Total Environ. 2020;765: 142753. https://doi.org/10.1016/j.scitotenv.2020.142753.
18. Nielsen MB. Identifying challenges and drivers for deployment of centralized biogas plants in Denmark. Sustainability. 2022. https://doi.org/10.3390/su14138021.
19. Mittal PS, Sinha N, Sithananthan PM, Maheshwari M. Assessing the potential of CBG as an alternative fuel: an experimental study on vehicle performance and emissions in BS VI compliant three-wheeler and passenger car. SAE Tech Paper Ser. 2024. https://doi.org/10.4271/2024-26-0076.
20. Singh D, Tembhare M, Kumar S. Compressed biogas plants in India: existing status, technological advances and challenges. Biomass Bioenerg. 2023;178(July): 106964. https://doi.org/10.1016/j.biombioe.2023.106964.
21. Singh D, Tembhare M, Machhirake N, Kumar S. Biogas generation potential of discarded food waste residue from ultra-processing activities at food manufacturing and packaging industry. Energy. 2023;263: 126138. https://doi.org/10.1016/j.energy.2022.126138.
22. Singh D, Tembhare M, Machhirake N, Kumar S. Impact of municipal solid waste landfill leachate on biogas production rate. J Environ Manage. 2023;336: 117643. https://doi.org/10.1016/j.jenvman.2023.117643.
23. Singh P, Kalamdhad AS. A comprehensive assessment of state-wise biogas potential and its utilization in India. Biomass Conversion Biorefinery. 2023;13(14):12557–79. https://doi.org/10.1007/s13399-021-02001-y.
24. Sirothiya M, Chavadi C. Compressed biogas (cbg) as an alternative and sustainable energy source in India: case study on implementation frameworks and challenges. Invertis J Renewable Energy. 2020;10:49–64. https://doi.org/10.5958/2454-7611.2020.00007.7.

25. Stürmer B, Leiers D, Anspach V, Brügging E, Scharfy D, Wissel T. Agricultural biogas production: a regional comparison of technical parameters. Renewable Energy. 2021;164:171–82. https://doi.org/10.1016/j.renene.2020.09.074.
26. Tavana M, Mousavi H, Khalili Nasr A, Mina H. A fuzzy weighted influence non-linear gauge system with application to advanced technology assessment at NASA. Expert Syst Appl. 2021;182(February): 115274. https://doi.org/10.1016/j.eswa.2021.115274.
27. Theuerl S, Herrmann C, Heiermann M, Grundmann P, Landwehr N, Kreidenweis U, Prochnow A. The future agricultural biogas plant in Germany: a vision. Energies. 2019. https://doi.org/10.3390/EN12030396.
28. Thiruselvi D, Kumar P, Kumar M, Lay C, Aathika S, Mani Y, Jagadiswary D, Dhanasekaran A, Shanmugam P, Sivanesan S, Show P. A critical review on global trends in biogas scenario with its up-gradation techniques for fuel cell and future perspectives. Int J Hydrogen Energy. 2020. https://doi.org/10.1016/j.ijhydene.2020.10.023.
29. UllahKhan I, Hafiz Dzarfan Othman M, Hashim H, Matsuura T, Ismail AF, Rezaei-Dasht Arzhandi M, Wan Azelee I. Biogas as a renewable energy fuel—a review of biogas upgrading, utilisation and storage. Energy Convers Manage. 2017;150(August):277–94. https://doi.org/10.1016/j.enconman.2017.08.035.
30. Wang Q, Xia C, Alagumalai K, ThanhNhi Le T, Yuan Y, Khademi T, Berkani M, Lu H. Biogas generation from biomass as a cleaner alternative towards a circular bioeconomy: artificial intelligence, challenges, and future insights. Fuel. 2023;333: 126456. https://doi.org/10.1016/j.fuel.2022.126456.
31. Wu D, Li L, Peng Y, Yang P, Peng X, Sun Y, Wang X. State indicators of anaerobic digestion: a critical review on process monitoring and diagnosis. Renewable Sustain Energy Rev. 2021;148: 111260. https://doi.org/10.1016/j.rser.2021.111260.
32. Wu D, Peng X, Li L, Yang P, Peng Y, Liu H, Wang X. Commercial biogas plants: review on operational parameters and guide for performance optimization. Fuel. 2021;303: 121282. https://doi.org/10.1016/j.fuel.2021.121282.
33. Yadav K, Sircar A. Fundamentals and developments of compressed biogas in city gas distribution network in India: a review. Petrol Res. 2022;7(3):409–18. https://doi.org/10.1016/j.ptlrs.2021.12.003.
34. Yang H, Li C, Shahidehpour M, Zhang C, Zhou B, Wu Q, Zhou L. Multistage expansion planning of integrated biogas and electric power delivery system considering the regional availability of biomass. IEEE Trans Sustain Energy. 2021;12:920–30. https://doi.org/10.1109/TSTE.2020.3025831.
35. Yeganeh R, Mohammadfam I, Soltanian A, Mirzaei Aliabadi M. An integrative fuzzy Delphi decision-making trial and evaluation laboratory (DEMATEL) study on the risk perception-influencing factors. Int J Occup Saf Ergon. 2022. https://doi.org/10.1080/10803548.2022.2112446.
36. Sakthivel P, Mittal N, Sinha P, Sithananthan M, Maheshwari M. Assessing the potential of CBG as an alternative fuel: an experimental study on vehicle performance and emissions in BS VI compliant three-wheeler and passenger car. SAE Technical Paper Series. 2024. https://doi.org/10.4271/2024-26-0076.
37. Mittal S, Ahlgren E, Shukla P. Barriers to biogas dissemination in India: a review. Energy Policy. 2018;112:361–70. https://doi.org/10.1016/J.ENPOL.2017.10.027.
38. Moeuf A, Lamouri S, Pellerin R, Tamayo-Giraldo S, Tobon-Valencia E, Eburdy R. Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs. Int J Prod Res. 2020;58(5):1384–400. https://doi.org/10.1080/00207543.2019.1636323.
39. Okoli C, Pawlowski SD. The Delphi method as a research tool: an example, design considerations and applications. Inf Manag. 2004;42(1):15–29. https://doi.org/10.1016/j.im.2003.11.002.
40. Mukeshimana M, Zhao Z, Ahmad M, Irfan M. Analysis on barriers to biogas dissemination in Rwanda: AHP approach. Renew Energy. 2021;163:1127–37. https://doi.org/10.1016/J.RENENE.2020.09.051.
41. Ahmad Zamzuri MI, Naserrudin NA, Ali NKM, Aziz SA, Rashid MFA, Dapari R, Ramdzan AR, Hod R, Hassan MR. "best of Both World": the amalgamation of fuzzy delphi method with nominal group technique for dengue risk prioritisation decision-making. J Func Spaces. 2022. https://doi.org/10.1155/2022/9581367.