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RESEARCH ARTICLE

Analyzing the barriers for aquaponics adoption using integrated BWM and fuzzy DEMATEL approach in Indian context

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Abstract
Aquaponic system in greenhouses which can recycle and reuse the water and nutrients is gaining importance across the world to counter the uncertainties due to weather fluctuations. However, there is a slow pace of growth in aquaculture practices around the globe in general and India in particular. There are many barriers to adopt the aquaponic culture. In this study an analysis of the barriers for aquaponics culture in Indian context during the COVID-19 period is presented. Literature review and interactions with various stakeholders help to find out the list of potential factors while gauging the success of their prospective aquaponics project. The "best-worst" methodology (BWM) is employed for ranking of barriers, whereas categorizing of barriers is carried out with the help of fuzzy DEMATEL. Furthermore, the results of this research work are of great value to corporations or start-up companies looking to invest in this technology as well as to farmers who wish to adopt this farming technique.

Keyword India · Sustainable farming Aquaponics · Barriers · Fuzzy DEMATEL

Introduction

One of the great lessons COVID-19 has taught us is that food security should be the most important priority at all levels: at family, local, state, and country levels. No one should depend entirely on others when crisis of that magnitude occurs. COVID-19 pandemic has taken as wake-up call to rethink and redesign our food systems (Bhavani and Gopinath 2020; Singh et al. 2021). It has been made clear that food production systems should be robust so that food is produced adequately and people have access to it during the time of crisis. During the last few decades when globalization occurred at a rapid pace, many countries were rushing on certain areas which gave better revenues through trade. They were shifting to other businesses from the food production sector or agriculture considering it as one of the least profitable sectors. Even the agriculture became more export-based. It brought big changes in the world including rural areas. Many people left the villages stopping the farming to migrate to cities where they could find jobs and enjoy better life. Some countries put ban on selling agriculture products (Jain et al. 2020). More than that COVID-19 resulted in millions of job losses. Most of those who lost their jobs have gone back to do the farming realizing that agriculture is the ultimate destination when the situation gets worse.

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India has always been a country where its majority (58%) of population depend on agriculture for their livelihoods (IBEF 2020). The growth rate and gross value added (GVA) by agriculture and allied sectors had improved from − 0.2% in 2015 to + 6.3% in 2017 with some improvement (+2.9%) in 2019 (Government of India 2019). This variation is due to the dependence on the monsoon, inefficient irrigation, injudicious and uncontrolled use of soil nutrients resulting in loss of fertility of soil, uneven access to modern technology in different parts of the country, and various other factors (Kala et al. 2018).

Despite all the rich farming culture and produce, Indian agriculture still has scope for improvement in terms of sustainable production. There is a need for promoting modern technologies and reforming agricultural research and extension as there was underfunding of infrastructure and operations, and limited access to state-of-the-art technologies in the past (World Bank 2012). The adaptation of a modern agriculture technique such as aquaponics can help in achieving the sustainable development goal.

Aquaponics in the simplest form is described as the fusion of two leading modern farming techniques, namely *Aquaculture* and *Hydroponics*. Aquaculture is the cultivation of fish and other organisms in a controlled environment while hydroponics is a soil-less farming method where crops are grown on water itself (Somerville et al. 2014). In aquaponics, the undigested and uneaten food of fishes mostly accumulated as ammoniacal nitrogen provide necessary nitrogen to plants for their growth after bacteria convert it to nitrates, and the plants perform their role by absorbing nitrates from the water, thus making it safe and clean enough for fishes to grow in. The water is re-circulated back to the fish tanks and the cycle repeats again and again. Therefore, aquaponics is one of the best examples of micro unit of a natural world wherein relationship among human, animals, plants, and microbes persists; importance of it has been recently realized and highlighted due to COVID-19 (Altieri and Nicholls 2020).

The soil-less feature of aquaponics not only reduces the dependence on availability of rich fertile soil for cultivation, but eliminates the limitation of agriculture being performed on land altogether. Thus, agricultural practices no longer need to be restricted on soil as now they can be performed easily on rooftops, basements, etc. This practice reduces the need for fertilizers or manure as plants obtain their nutrition directly from the fish excretes. The approximate decrease of about 90% of water requirement not only removes the dependence on monsoon for agriculture but opens up new avenues for performing agriculture in areas prone to droughts or areas with depleting groundwater levels (Simanovski and Pirkebner 2018).

To mitigate the adverse effects of nature, aquaponics has been rising in many parts of India like in Cherai, a village in Kochi, Kerala (Karthika 2018), and outside India like Wellington, New Zealand (WWF 2013). In Kerala, many farmers have paired the technology with rooftop solar panels to ensure continuous power supply and to utilize the full potential of the integrated system. Even though the Indian project started just 4 years back, many farmers have been successful in growing vegetables in hundred bags by using 14,000-L fish tanks, which contain more than 1500 fish. This technique has benefited farmers and fishermen alike. The practice of aquaponics has various incentives including organic-like produce, soil-less nature, zero fertilizer use, higher control, being extremely water-efficient and making farming possible on non-arable small piece of land. Because of its ability to be installed in different landscapes especially in backyard gardens, numerous aquaponics setups have also been installed on rooftops in the West Bank and Gaza Strip, by the Food and Agriculture Organization of the United Nations (Somerville et al. 2014). These setups are in effect to tackle the chronic food and nutrition security issues seen across the region. It became so attractive to individual families during lock-downs due to COVID-19.

Aquaponics technology finds its origins during the times of the Aztec Indians, but as a modern technology, it is still in the research and development phase. There have been many studies and researches about how to improve the crop yield, how to incorporate new methodologies in aquaponics, and other technological developments (Monsees et al. 2017; Yang and Kim 2019). One such study advocates the introduction of a vital index like nitrogen utilization efficiency (NUE), for the assessment of aquaponics and the improvement of the system through micro- and macro-nutrient addition (Ru et al. 2017). There also have been some comparative studies between aquaponics and conventional farming, stating that increased productivity and water use efficiency are the key advantages of modern farming technologies like aquaponics (Alshrouf 2017). There are studies in different parts of the world which compare the final produce of the different agricultural technologies to dismiss the safety concerns about fish and plant cycle integration and conclude that aquaponics can be considered a strong alternative to conventional farming (El-Essawy et al. 2019; Rosgren and Grahler 2022). A vision document prepared for Washington DC and Netherland emphasized to capture the full potential of a symbiotic that effectively integrates the value of nature into the urban scape and its social, built, and geographic characteristics (Stuiver and O'hara 2022).

Beyond the hype of the technology, there are several challenges associated with the implementation of aquaponics such as lack of knowledge and expertise, lack of capital investment, poor pest and disease management, and others (Love et al. 2014; Turnsek et al. 2020; Yep and Zheng 2019). Some factors are more important than others in different climatic, geographical, and socio-economic contexts.

Technological, economic, and social considerations are crucial in setting up, wide-scale adoption, and in-turn success of the aquaponics technology. Many studies have focused on the diversity of these fields that need to be addressed including various technological, socio-economic, and system design trends (Goddek et al. 2015; Junge etal. 2017; Turnsek et al. 2020)

However, there is a lack of qualitative research on the barriers to the adoption of aquaponics culture across the India and especially during the COVID-19, as the people were not much aware about its exhaustive application. Thus, there was the potential to identify the barrier and their remedial action for efficient and effective utilization of aquaponics environment. From the literature review, it can be concluded that the previous researches were mainly focused on the technical aspects of the aquaponics setup, less on the economic front, and even lesser considerations of the social aspects. Moreover, those studies were not exhaustive in listing the challenges and they did not employ any scientific decision-making tool to rank and categorize them. The present study focused on the barriers that are significant and that should be considered while setting up an aquaponics unit. This research aimed at identifying numerous challenges under the domain of economic, technological, social, educational, etc. that are crucial in determining the success of aquaponics in Indian context. More importantly, all these factors have been ranked according to their importance or the priority of their consideration, using a best-worst method (BWM). The factors are also categorized into cause-and-effect groups using fuzzy DEMATEL approach. Addressing all the mentioned challenges, the incorporation of aquaponics into the current farming scenario would see a phenomenal rise in both efficiency and productivity of the agricultural sector. Thus, this setup provides a sustainable modern farming technique that shall boost the agricultural sector to its highest potential.

This research paper presents the current research scenario of aquaponics, its research gaps and challenges identified through literature review and expert interviews. It also describes fuzzy DEMATEL tool which uses best-worst method of ranking and helps compare among the categories. Finally, it concludes and recommends important areas for future research.

Barriers in adoption of aquaponics

The following list of barriers have been created by extensive literature review and expert interviews.

Lack of knowledge and expertise

Aquaponics requires a symbiotic environment with appropriate levels of pH, temperature, oxygen levels, etc. in accordance with the life forms of animals and plants. This requires high-level expertise not just in the field of farming and fish culture but also in the fields of basic sciences and biological systems. This proves to be a significant barrier in India due to lack of knowledge and awareness among various stakeholders, especially farmers and extension workers. Studies conducted even in developed counties such as Canada and UK showed that there is lack of knowledge and expertise and it serves as a significant barrier to implementation of aquaponics (Matthews 2017; Cammies 2021). Although highly qualified people are involved in aquaponics in European countries as it is evident from a survey conducted in Europe on current aquaponics systems showed that 91.7% of the people involved in aquaponics hold at least post-graduate degree (Villarroel et al. 2016).

Absence of stable environment

There are different climatic conditions which are specific to the species grown, their age, size, technology, etc. that determine the success of any aquaponic system. Whatever these conditions may be, they vary to a great extent by season throughout the year and these fluctuations might have a considerable impact on the health and growth of animals and plants used in aquaponics system (Goddek et al. 2015). Fluctuations in temperature specifically have a tremendous impact on the fish, plant, and bacteria cycles and the nitrification process as well (Zhu and Chen 2002). In a study conducted in Brazil, it was observed that absence of stable environment is one of the barriers to the success of aquaponics (Brewer et al. 2021).

High capital requirements

The initial investments and operating expenses of initiating and running an aquaponic unit are also barriers to the success of the technology (Matthews 2017). Despite considerable research in the area, it is still uncertain whether the aquaponics is economically profitable (Greenfeld et al. 2019). Though studies are being conducted to explore more cost-effective ways to implement aquaponics, they are still a long way to go to become a good option for commercial ventures (Sunny et al. 2019).

Nutrient limitation in fish excreta

In a closed loop aquaponics system, plants derive almost all of their nutrients from the fish excreta. However, certain essential nutrients like Fe, Ca, Mg, and K which are required for the plant growth (Njinga et al. 2013) are limited in the fish excreta and fish meals since fishes have minimal usage of these metals (Savidov et al. 2007). Synthetic fertilizers may be used to compensate these deficiencies but aquaponic systems rely little on them (Yep and Zheng 2019). Surveys show that some aquaponics practitioners also have problems in understanding and managing these nutrient deficiencies (Matthews 2017).

Maintaining pH

The life forms in the aquaponics unit, i.e., fishes, plants, and microbes, have different optimal pH ranges (Somerville et al. 2014). Given the difference in pH ranges, there is no single value of pH that would ensure optimal growth of all the involved species. There is a constant influx of acid ($H+$) from the nitrification of ammonia and of hydroxide ($OH-$) or bicarbonate from most plants, both of which keep on trying to shift the pH from the decided value (Yep and Zheng 2019). The working pH is based on trade-off between the growth of one organism at the cost of the other organism and thus has to be carefully decided and maintained (Yep and Zheng 2019).

Poor pest and disease management

The pest and disease management front is another aspect that poses as a barrier for the aquaponic systems (Vermeulen and Kamstra 2013). There is a need for innovative pest and disease management solutions which do not disturb the balance of the cycle. The pest prevention solutions have to be in accordance with the fishes so as to not harm them and the antibiotics have to be suitable for the plants for similar reasons (Goddek et al. 2015).

Interrupted power supply

Aquaponics setup requires continuous electricity for aeration, water pumps, and possibly temperature regulation systems (Matthews 2017). A survey of aquaponic practitioners in the USA and internationally shows that about 95% of the respondents relied on power from the main supply grid but because of its unreliability, about 57% of the respondents used alternate sources of renewable energy, e.g., solar cells (Love et al. 2014). This adds to which is already high capital investment of the aquaponics setup and thus restricts its adoption and expansion.

Limited plant and fish combinations

In an aquaponic setup with multiple living organisms, it is difficult to set one value for each water quality parameter that would suit all the organisms living within the system (Estim et al. 2020). Thus, these parameters have to be maintained within the tolerance levels of each organism (Estim et al. 2020). This leads to sub-optimal conditions for individual organisms but aims to optimize the overall harvest. Even today, finding appropriate fish and plant combinations that would have an optimal yield while trading off and growing at these sub-optimal conditions is a key challenge (König et al. 2018). This problem is enhanced further when market restraints are applied as the pool of crops that could be grown in the system is further narrowed.

Limited options of crops to be produced

Aquaponics as a technology is capable of producing numerous types of crops commercially. But practically it is restricted to producing only few high- and middle-value crops like tomatoes and lettuces. This is so, because the returns in producing low-value crops like potatoes fall short to cover the cost incurred to establish the aquaponic setup per unit space. Since the low-value crops form a significant part of the diet, the inability to produce them profitably accompanied by availability of cheap counterparts, limits the market of aquaponic products thereby the possibility of adoption and growth (Mukherjee 2019; Turnšek et al. 2019). The summary of barriers identified based on literature review is presented in Table 1.

Studies pertaining to the applicability of aquaponics and the barriers that are associated with it are not exhaustive. They fall short to account for various technical and sociological parameters which are significant in determining the success of aquaponics. Moreover, no current research has conducted scientific studies that employs decision-making tools to categorize the challenges in implementing the aquaponics in Indian context.

Methodology

The challenges in implementation of aquaponics in Indian context are identified on the basis of extensive literature review and discussion with the domain experts. In further analysis, best-worst method (BWM) developed by Razaei (2015) is used for prioritizations of the barriers and fuzzy DEMATEL is employed for further categorization of barriers into cause and effect groups.

There are many Multi Criteria Decision Making (MCDM) methods available in literature for ranking such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Esfandiari and Rizvandi 2014), Analytic Hierarchy Process (AHP) (Cheng et al. 1999), and Grey Weighted Sum Model (GWSM) (Esangbedo and Che 2016). However, BWM is chosen for this study as it requires less comparison data and provides a more consistent result (Rezaei 2015), which not only reduces the number of pairwise comparisons and inconsistency in such a task (Labella et al. 2021) but it also performs better than other multi-attribute decision-making models (Bai 2018.)

Table 1 List of barriers in adoption of aquaponics based on the literature survey

Code	Name of barrier	Description	Country	Source
B1	Lack of knowledge and expertise	Educated and expert labor is required to run the system and maintain a balance of all water quality parameters.	Canada	(Matthews 2017)
B2	Absence of stable environment	Fluctuating environmental conditions will impact the system negatively. Stable environment is preferred.	United States	(Zhu and Chen 2002)
B3	High capital requirements	Huge initial investments and ongoing expenditures make the projects risky.	Canada	(Matthews 2017)
B4	Nutrient limitation in fish excreta	Plants cannot always derive all the nutrients from fish excreta; external help might be required.	Berlin, Spain, Switzerland	(König et al. 2018)
B5	Maintaining pH	Maintaining one pH value which is favorable for all organisms in the system is challenging	Canada	(Yep and Zheng 2019)
B6	Poor pest and disease management	Conventional pest and disease management techniques do not work in the aquaponics setup. New techniques need to be developed and implemented.	Germany, Belgium, Iceland	(Goddek et al. 2015)
B7	Interrupted power supply	Continuous electricity supply at all times is difficult to ensure. Fail-safes and alternate sources add to the already high capital expenditures.	Canada	(Matthews 2017)
B8	Limited plant and fish combinations	Finding a combination of plants and fishes that have a common range for all water quality parameters for their optimal growth is difficult to find.	Berlin, Spain, Switzerland	(König et al. 2018)
B9	Limited options of crops to be produced	Not all market crops can be grown economically through aquaponics.	India	Self-developed

Commonly used methods for categorization of factors are Analytic Network Process (ANP) (Lee et al. 2013), Interpretive Structural Modelling (ISM) (Al-Muftah et al. 2018; Nagpal et al. 2017; Pitchaimuthu et al. 2019), and Interpolative Boolean Algebra (IBA) (Mandic and Delibasic 2014). The DEMATEL method not only converts the interdependency relationships into a cause and effect group via matrixes but also finds the critical factors of a complex structure system with the help of an impact relation diagram (Si et al. 2018). However, fuzzy DEMATEL is selected for this work as it ranks factors and also finds out the critical evaluation criteria as well as the mutual influence of various factors on each other (Si et al. 2018).

The procedures for BWM and fuzzy DEMATEL are detailed in the following:

Best-worst method (BWM)

Best-worst method determines weights of factors in reduced number of comparisons. The factor with the most vital role is considered most important which becomes evident on the basis of weights determined by BWM method.

Steps involved in BWM:

Step 1: Criteria determination

In the present study there are 9 barriers, denoted by B_1, B_2, B_3……. B_9. Select one best criteria (most desirable/most important) and one worst criteria (least desirable/least important) based on the opinion of industry experts.

Step 2: Comparing best and worst criteria

Assign preference values (preference is indicated by a number 1 to 9, where 1 denotes equal importance) after comparing the most important barrier with all barriers denoted by p_{m1}, p_{m2}, p_{m3}, ...p_{m9}. Similarly compare the least important barrier with all barriers and assign a quantitative preference value to each barrier denoted as p_{1l}, p_{2l}, p_{3l}, ... p_9.

Step 3: Optimal weight calculation

Let weights of barriers B_1, B_2, B_3……. B_9 be denoted by α_1, α_2, α_3…… α_9. After assigning preference values, obtain optimal weights by solving the linear programming model from Eqs. (1)–(4) (Rezaei 2015)

Objective: Minimize β

Subject to:

$$\left|\frac{\alpha_m}{\alpha_j} - p_{mj}\right| \leq \beta \qquad j = 1, 2, 3 \ldots, 9 \tag{1}$$

α_m : denotes the weight of the most important factor as selected in step 1.

$$\left|\frac{\alpha_j}{\alpha_l} - p_{jl}\right| \leq \beta \qquad j = 1, 2, 3. \ldots, 9 \quad (2)$$

α_l : denotes the weight of least important factor as selected in step 2.

$$\sum_{j=1}^{9} \alpha_j = 1 \qquad j = 1, 2, 3 \ldots .9 \quad (3)$$

(Equation 3 is the expression denoting the sum of weights is equal to unity.)

$$\alpha_j \geq 0 \qquad j = 1, 2, 3 \ldots .9 \quad (4)$$

Step 4: Solving equations

On solving the linear equations, we get the weights for all 9 barriers on the basis of which they are ranked.

The fuzzy DEMATEL method

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method was first introduced by the Geneva Research Centre of the Battelle Memorial Institute to visualize the structure of complicated causal relationships through matrices or digraphs (Gabus and Fontela 1973). Fuzzy DEMATEL method is employed in order to visualize the problem within a fuzzy environment. In the present study we use the fuzzy DEMATEL method to categorize the barriers in implementation of aquaponics into two categories, the cause group and the effect group. It helps in determining the relative importance of the factors and thereby ranking/prioritizing them.

DEMATEL method is used to understand the relationship between various factors and analyze how they influence each other. This method of ranking had been used previously in many domains such as improvising emergency systems (Han and Deng 2018), barriers to coastal shipping development (Venkatesh et al. 2017), remanufacturing industry (Bhatia and Srivastava 2018), supplier selection (Chang et al. 2011), and safety management system for airlines (Liou et al. 2008). In this method directed graphs are employed, which help in separating the factors into two groups, the cause group and the effect group. DEMATEL method also aids the making of causal diagram which helps in visualizing the groups and their influence on other factors.

Fuzzy logic was proposed by Zadeh (1965). He introduced the concept of fuzzy set theory and the concept of membership function (Zadeh 1965). A membership function defines the degree of truth in the logic. The membership function in fuzzy logic plays a vital role in selecting the best alternative among the feasible one, when applied to any research problem. However, in literature, a number of membership functions are reported with their application, advantages, and limitations, among which the response of triangular membership function out performed to other membership functions (Zhao and Bose 2002). Thus, in this study, a triangular membership function is selected for further analysis (Fig. 1). In order to obtain crisp values, defuzzification is done using the center of area (COA) method also known as the centroid method.

The procedure of fuzzy DEMATEL method uses reviews of domain experts to form the initial matrix (Lin and Wu 2008). All the experts were presented with 9 factors/challenges in implementation of aquaponics in India. The challenges are denoted as B_1, B_2, B_3……. B_9. Each expert graded the factors based on relative importance between 0 and 4 as denoted in Table 31 (Appendix 3).

Step 1: Direct relation matrix (D_m)

A direct relation matrix (D_m) is formed on the basis of influence score given by domain experts.

Step 2: Transform in triangular fuzzy numbers

The influence scores in the direct relation matrix (D_m) are replaced by the corresponding triangular fuzzy numbers as given in Table 2.

Step 3: Defuzzification of matrix (Z_m)

In order to convert the triangular fuzzy numbers to crisp values, the given matrix is now defuzzified by centroid method using Eq. (5) (Liou et al. 2008; Si et al. 2018).

$$\left(CV_{ij}\right) = \frac{S_{ij} + M_{ij} + L_{ij}}{3} \mathrm{i} = 1, 2, 3 \ldots ..9; \mathrm{j} = 1, 2, 3 \ldots ..9 \quad (5)$$

CV_{ij} : denotes the crisp value for the particular cell i, j.

S_{ij} : denotes the smallest likely value of the particular cell i, j.

M_{ij} : denotes the most probable value of the particular call i, j.

L_{ij} : denotes the largest possible value of the particular cell i, j.

Step 4: Form a single matrix (S_m)

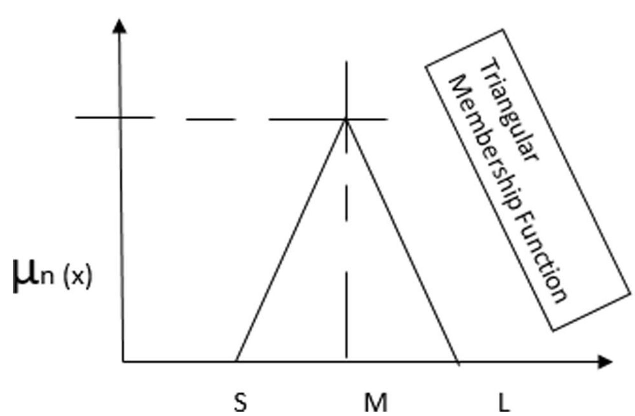

Fig. 1 Triangular membership function. $\mu_{n(x)}$, membership function; *S*, smallest likely value; *M*, most probable value; *L*, largest possible value

Table 2 Comparison of most important criterion with all criteria

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
B_1	1	3	2	5	6	8	7	4	9

Until now individual matrices of experts were formulated separately, but now one single matrix (S_m) is obtained by averaging corresponding cells of all the matrices using Eqs. (6)–(8) (Lin and Wu 2008).

$$S_m = \frac{Z_{m_{ij}}^{<1>} + Z_{m_{ij}}^{<2>} + Z_{m_{ij}}^{<3>} + \cdots + Z_{m_{ij}}^{<N>}}{N_e} \quad (6)$$

$Z_{m_{ij}}^{<N>}$: denotes the value crisp value in the cell i, j of the defuzzified matrix of N^{th} expert.

$$S_m = \left[NV_{11}NV_{12} \cdots NV_{19} \vdots \ddots \vdots NV_{91}NV_{92} \cdots NV_{99}\right] \quad (7)$$

$$NV_{ij} = \frac{\sum_{g=1}^{N_e} OV_{ij}^{<g>}}{N_e} \quad i = 1,2,3 \ldots .9; \ j = 1,2,3 \ldots ..9 \quad (8)$$

NV_{ij} : denotes the new crisp value in the cell i, j in the single matrix.

$OV_{ij}^{<N>}$: denotes the crisp value in the cell i, j corresponding to N^{th} matrix.

N_e : denotes the number of experts.

Step 5: Normalized direct relation matrix (G_m)

The single direct relation matrix (S_m) is normalized/generalized using Eqs. (9) and (10) (Lin and Wu 2008).

$$G_m = X * S_m \quad (9)$$

$$X = \frac{1}{\sum_{j=1}^{9} NV_{ij}} i = 1,2,3 \ldots .9; j = 1,2,3 \ldots ..9 \quad (10)$$

Step 6: Total relation matrix (Y_m)

Normalized direct relation matrix (G_m) is formulated using Eq. (11) in order to obtain the total relation matrix (Y_m) (Lin and Wu 2008).

$$Y_m = G_m * \left(I_m - G_m\right)^{-1} \quad (11)$$

I_m : denotes the Identity matrix.

Step 7: Obtain sum of rows and columns:

Sum of rows (U_i) is calculated using Eq. (12), and similarly, sum of columns (V_j) is calculated using Eq. (13) (Wang and Chen 2012).

$$U_i = \sum_{j=1}^{9} Y_{mij} i = 1,2,3 \ldots .9; \ j = 1,2,3 \ldots ..9 \quad (12)$$

$$V_j = \sum_{i=1}^{9} Y_{mij} \ i = 1,2,3 \ldots .9; \ j = 1,2,3 \ldots ..9 \quad (13)$$

Y_{mij} : denotes the value in the cell i, j of the Total relation matrix (Y_m).

Step 8: Causal diagram

(U_i+V_j) and (U_i-V_j) are calculated for equal values of i and j followed by a graphical depiction with (U_i+V_j) on the X-axis and (U_i-V_j) on the Y-axis, known as the causal diagram (Lin and Wu 2008; Liou et al. 2008).

A case illustration

In this research work, a case of Indian context is considered and the data were collected during the COVID-19. This section is categorized into three sub-section, viz, "Data collection", "Ranking by BWM", and "Categorization by fuzzy DEMATEL" respectively.

Data collection

The questionnaires for ranking and cause-effect categorization of the barriers for aquaponics adoption using integrated BWM and fuzzy DEMATEL approach (Appendix 1 and Appendix 3) were finalized after a review by six experts (Appendix 1). Out of the six experts selected for this study, two are from academia, two from the industry, and two from not-for-profit organization. Their inputs helped to figure out one important barrier for this study, which resulted in a final list of nine barriers. The experts also helped in validation of the literature review findings and also facilitated framing the questionnaire more specific to the Indian context. They commented on the intelligibility, subject, and illustration of the survey questionnaire. Suggestions were incorporated and improvements in the questionnaire were completed before distributing for data collection. The final questionnaires consist of all the nine significant challenges identified through extensive literature review and inputs from experts.

The data for questionnaires (Appendix 2: Table 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28 and 29) was collected from six experts (Appendix 1) and used for BWM method. Pairwise comparison data was obtained on a scale of 1 to 9 for comparison of best to others and worst to others.

The data for questionnaire (Appendix 3: Table 30, 31 and 32) was obtained though survey method. Google form was chosen as a medium to collect data from professionals who are linked directly or indirectly to aquaponics industry. Initially, 200 emails were sent to the professionals who are working in operations, strategy, marketing, and environment domain. Out of the 200 emails sent, approximately 100 responses were received. Half of the emails received were either incomplete or not appropriate for the purpose of analysis. Overall, 50 responses received were carefully analyzed and checked for anomalies/errors, and minor corrections were made after checking with the respondent. The professionals were asked to rate these challenges on a 5-point Likert scale (e.g., 1 = no influence and 5 = extremely high influence) illustrating the influence of each challenge on setting up of an aquaponics setup in India. The average of the valid responses was used to generate the pairwise comparison matrix of the selected barriers. After processing all the responses, the fuzzy DEMATEL approach was used for cause-effect categorization of barriers.

Ranking by BWM

In the present study, nine barriers, as identified from the literature and through expert feedback, are being utilized in the implementation of aquaponics in Indian context. After receiving the expert's feedback, the proposed best-worst method was applied for calculating the weights of respective barriers. Table 2 and Table 3 represent the input from all 6 experts for barriers B1 and B9 respectively. In the similar manner, the comparison was made in respect of other barriers. The values represent the average of all the responses rounded off to nearest integer. This data is further utilized for constructing the matrix in Table 4.

Now a linear programming model is formed using Eqs. (1) to (4). The equations obtained (1a) to (4a) are then solved in order to obtain the weights of respective barriers.

$$\left|\frac{\alpha_1}{\alpha_2} - 3\right| \le \beta \tag{1a}$$

$$\left|\frac{\alpha_1}{\alpha_3} - 2\right| \le \beta \tag{1b}$$

$$\left|\frac{\alpha_1}{\alpha_4} - 5\right| \le \beta \tag{1c}$$

$$\left|\frac{\alpha_1}{\alpha_5} - 6\right| \le \beta \tag{1d}$$

$$\left|\frac{\alpha_1}{\alpha_6} - 8\right| \le \beta \tag{1e}$$

$$\left|\frac{\alpha_1}{\alpha_7} - 7\right| \le \beta \tag{1f}$$

$$\left|\frac{\alpha_1}{\alpha_8} - 4\right| \le \beta \tag{1g}$$

$$\left|\frac{\alpha_1}{\alpha_9} - 9\right| \le \beta \tag{1h}$$

$$\left|\frac{\alpha_2}{\alpha_9} - 7\right| \le \beta \tag{2a}$$

$$\left|\frac{\alpha_3}{\alpha_9} - 8\right| \le \beta \tag{2b}$$

$$\left|\frac{\alpha_4}{\alpha_9} - 5\right| \le \beta \tag{2c}$$

$$\left|\frac{\alpha_5}{\alpha_9} - 3\right| \le \beta \tag{2d}$$

$$\left|\frac{\alpha_6}{\alpha_9} - 2\right| \le \beta \tag{2e}$$

$$\left|\frac{\alpha_7}{\alpha_9} - 3\right| \le \beta \tag{2f}$$

$$\left|\frac{\alpha_8}{\alpha_9} - 6\right| \le \beta \tag{2g}$$

$$\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \alpha_7 + \alpha_8 + \alpha_9 = 1 \tag{3a}$$

Table 3 Comparison of least important criterion with all criteria

	B_9
B_1	9
B_2	7
B_3	8
B_4	5
B_5	3
B_6	2
B_7	3
B_8	6
B_9	1

Table 4 Weights and ranking of criteria

Criteria	B_1 α_1	B_2 α_2	B_3 α_3	B_4 α_4	B_5 α_5	B_6 α_6	B_7 α_7	B_8 α_8	B_9 α_9
Weights	0.3146	0.1277	0.1915	0.0766	0.0638	0.0479	0.0547	0.0957	0.0273
Ranking	1	3	2	5	6	8	7	4	9

$$\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7, \alpha_8, \alpha_9 \geq 0 \quad (4a)$$

On solving the above equations, the weights are obtained and are further used to rank the barriers as shown in Table 4.

Table 4 depicts that the Lack of knowledge and expertise (B_1) has the highest weight (α_1) 0.3146 while Limited option of crops to be produced (B_9) has the lowest weight (α_9) 0.0273. Since $\alpha_1 > \alpha_3 > \alpha_2 > \alpha_8 > \alpha_4 > \alpha_5 > \alpha_7 > \alpha_6 > \alpha_9$, therefore $B_1 > B_3 > B_2 > B_8 > B_4 > B_5 > B_7 > B_6 > B_9$ are the ranks of importance.

Categorization by fuzzy DEMATEL

After ranking the barriers, fuzzy DEMATEL is applied for categorizing the barriers into cause-and-effect group. The procedural steps are applied as explained in the "Methodology" section, initially a questionnaire was prepared with the help of experts (Appendix 1), and survey method was employed for the data collection to prepare the direct-relation matrix containing the average influence scores given by 50 survey respondents. The values represent the average of all the responses rounded off to nearest integer. This data is further utilized for constructing the matrix in Table 5.

Now the influence scores in Table 5 are replaced by respective triangular fuzzy numbers using Table 31 (Appendix 3) as shown in Table 6.

The next step is to defuzzify the values in Table 6 and convert them into crisp values. This defuzzification is done by applying the centroid method using Eq. (5). The crisp values obtained after defuzzification are shown in Table 7.

Now a single matrix is formed using all the processed matrices of the domain-experts (i.e., Six, as mentioned in Appendix 1); this formation of single matrix is done using Eqs. (6), (7), and (8). This single matrix is shown in Table 8.

The next step is to normalize/generalize the single matrix in Table 8, using Eqs. (9) and (10). This results in normalized direct relation matrix as shown in Table 9.

Normalized total relation matrix is formulated using Eq. (11) and total relation matrix is obtained as shown in Table 10.

From the total relation matrix, sum of rows (U_i) and sum of columns (Vj) are calculated using Eqs. (12) and (13). The next step is to form the causal diagram by plotting ($U_i + V_j$) on the X-axis and ($U_i - V_j$) on the Y-axis as shown in Fig. 2. The degree of central role is shown in Table 11.

The barriers were arranged and ranked on the basis of their respective weights as shown in Table 4. Lack of knowledge and expertise (B_1) has the highest weight (α_1) 0.3146 while Limited option of crops to be produced (B_9) has the lowest weight (α_9) 0.0273. Since $\alpha_1 > \alpha_3 > \alpha_2 > \alpha_8 > \alpha_4 > \alpha_5 > \alpha_7 > \alpha_6 > \alpha_9$, therefore $B_1 > B_3 > B_2 > B_8 > B_4 > B_5 > B_7 > B_6 > B_9$ are the ranks of importance.

These results are consistent with the existing literature wherein lack of knowledge and expertise and high capital requirements are two of the most prominent challenges in setting up an aquaponics unit (Brewer 2019; Greenfeld et al. 2020). Farmers with lack of knowledge and lack of information about aquaponics accounted for a huge proportion of farmers, out of which about half had financial concerns about initial capital requirements as well (Brewer 2019). Absence of stable environment, limited fish and plant combinations restricting the expansion of production, and other technical challenges constitute the next prominent set of challenges in setting up an aquaponics unit (Brewer 2019; Goddek et al. 2015).

According to Table 11, the value of ($U_i + V_j$) denotes the importance of the barrier. Lack of knowledge and expertise (B_1) has the highest ($U_i + V_j$) score of 7.0817, followed by $B_3 > B_2 > B_8 > B_4 > B_5 > B_7 > B_6 > B_9$. Using the fuzzy DEMATEL method, the barriers are categorized into cause-and-effect groups using the ($U_i - V_j$) score. On the basis of ($U_i - V_j$) score, the evaluation barriers, namely, High capital requirements (B_3), Maintaining pH (B_5), Interrupted power supply (B_7), Limited plant and fish combinations (B_8), and Limited options of crops to be produced (B_9), fall under the category of cause group, whereas Lack of knowledge and expertise (B_1), Absence of stable environment (B_2), Nutrient limitation in fish excreta (B_4), and Poor pest and disease management (B_6) fall under the category of effect group.

The cause group factors have an impact on many other factors. Interrupted power supply (B_7) has the highest ($U_i - V_j$) value of 2.5395; hence, barrier B_7 has more impact on the

Table 5 Direct-relation matrix (Dm)

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
B_1	0	4	4	2	1	0	0	1	1
B_2	4	0	2	1	0	2	0	0	0
B_3	4	3	0	2	1	3	0	4	3
B_4	3	3	1	0	1	1	0	2	1
B_5	3	3	2	3	0	3	0	1	1
B_6	1	1	1	1	0	0	2	2	0
B_7	4	4	3	3	3	2	0	2	0
B_8	4	3	3	2	2	2	0	0	0
B_9	3	4	2	0	0	2	0	0	0

Table 6 Triangular fuzzy numbers

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
B_1	0	(0.6, 0.75, 1)	(0.6, 0.75, 1)	(0.25, 0.5, 0.6)	(0.1, 0.25, 0.5)	(0, 0.1, 0.25)	(0, 0.1, 0.25)	(0.1, 0.25, 0.5)	(0.1, 0.25, 0.5)
B_2	(0.6, 0.75, 1)	0	(0.25, 0.5, 0.6)	(0.1, 0.25, 0.5)	(0, 0.1, 0.25)	(0.25, 0.5, 0.6)	(0, 0.1, 0.25)	(0, 0.1, 0.25)	(0, 0.1, 0.25)
B_3	(0.6, 0.75, 1)	(0.5, 0.6, 0.75)	0	(0.25, 0.5, 0.6)	(0.1, 0.25, 0.5)	(0.5, 0.6, 0.75)	(0, 0.1, 0.25)	(0.6, 0.75, 1)	(0.5, 0.6, 0.75)
B_4	(0.5, 0.6, 0.75)	(0.5, 0.6, 0.75)	(0.1, 0.25, 0.5)	0	(0.1, 0.25, 0.5)	(0.1, 0.25, 0.5)	(0, 0.1, 0.25)	(0.25, 0.5, 0.6)	(0.1, 0.25, 0.5)
B_5	(0.5, 0.6, 0.75)	(0.5, 0.6, 0.75)	(0.25, 0.5, 0.6)	(0.5, 0.6, 0.75)	0	(0.5, 0.6, 0.75)	(0, 0.1, 0.25)	(0.1, 0.25, 0.5)	(0.1, 0.25, 0.5)
B_6	(0.1, 0.25, 0.5)	(0.1, 0.25, 0.5)	(0.1, 0.25, 0.5)	(0.1, 0.25, 0.5)	(0, 0.1, 0.25)	0	(0.25, 0.5, 0.6)	(0.25, 0.5, 0.6)	(0, 0.1, 0.25)
B_7	(0.6, 0.75, 1)	(0.6, 0.75, 1)	(0.5, 0.6, 0.75)	(0.5, 0.6, 0.75)	(0.5, 0.6, 0.75)	(0.25, 0.5, 0.6)	0	(0.25, 0.5, 0.6)	(0, 0.1, 0.25)
B_8	(0.6, 0.75, 1)	(0.5, 0.6, 0.75)	(0.5, 0.6, 0.75)	(0.25, 0.5, 0.6)	(0.25, 0.5, 0.6)	(0.25, 0.5, 0.6)	(0, 0.1, 0.25)	0	(0, 0.1, 0.25)
B_9	(0.5, 0.6, 0.75)	(0.6, 0.75, 1)	(0.25, 0.5, 0.6)	(0, 0.1, 0.25)	(0, 0.1, 0.25)	(0.25, 0.5, 0.6)	(0, 0.1, 0.25)	(0, 0.1, 0.25)	0

Table 7 Crisp values matrix (Zm)

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
B_1	0	0.7833	0.7833	0.45	0.2833	0.1167	0.1167	0.2833	0.2833
B_2	0.7833	0	0.45	0.2833	0.1167	0.45	0.1167	0.1167	0.1167
B_3	0.7833	0.6167	0	0.45	0.2833	0.6167	0.1167	0.7833	0.6167
B_4	0.6167	0.6167	0.2833	0	0.2833	0.2833	0.1167	0.45	0.2833
B_5	0.6167	0.6167	0.45	0.6167	0	0.6167	0.1167	0.2833	0.2833
B_6	0.2833	0.2833	0.2833	0.2833	0.1167	0	0.45	0.45	0.1167
B_7	0.7833	0.7833	0.6167	0.6167	0.6167	0.45	0	0.45	0.1167
B_8	0.7833	0.6167	0.6167	0.45	0.45	0.45	0.1167	0	0.1167
B_9	0.6167	0.7833	0.45	0.1167	0.1167	0.45	0.1167	0.1167	0

system and other challenges as interrupted power supply would directly affect the capital requirements, ability to sustain limited plant and fish combinations, etc.; however, the low $(U_i + V_j)$ score of 4.9165 for B_7 can be justified by the relative low occurrence of the challenge in aquaponics plants compared to other challenges (El-Sayed 2020). The last barrier in the list of cause group is High capital requirements (B3) with a $(U_i - V_j)$ score of 0.0115 and a high $(U_i + V_j)$ score of 6.7355 giving it a higher ranking in importance, which is consistent with the results from the best-worst method. The barriers categorized as the effect group are influenced by the other barriers. Absence of stable environment (B_2) has the lowest $(U_i - V_j)$ score of −2.1015 implying that barrier B_2 is influenced more compared to other factors. Lack of capital, lack of knowledge, and lack of appropriate plant and fish combination would all negatively affect the ability to provide stable environment for the aquaponics unit.

Conclusions

The present research identified nine criteria or the challenges in the implementation of aquaponics shortlisted considering the social, economic, and technical variables by aggregating the expert's inputs. When they were categorized using

Table 8 Single matrix (Sm)

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
B_1	0	0.7833	0.7278	0.45	0.2833	0.1167	0.1167	0.2278	0.2278
B_2	0.7278	0	0.3944	0.2833	0.1722	0.5056	0.1167	0.1722	0.1167
B_3	0.7833	0.5611	0	0.3944	0.1722	0.6167	0.1167	0.7278	0.5611
B_4	0.6722	0.6167	0.3389	0	0.3389	0.2833	0.1167	0.3944	0.3389
B_5	0.6722	0.6167	0.3944	0.5056	0	0.5611	0.1722	0.2278	0.2833
B_6	0.2833	0.2833	0.2278	0.2833	0.1167	0	0.3944	0.3944	0.1167
B_7	0.6722	0.7278	0.6167	0.6167	0.6722	0.3944	0	0.3944	0.1167
B_8	0.7278	0.7278	0.6167	0.45	0.5611	0.3944	0.1167	0	0.1167
B_9	0.6167	0.7278	0.45	0.1167	0.1722	0.45	0.1167	0.1167	0

Table 9 Normalized direct relation matrix (Gm)

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
B_1	0	0.1860	0.1728	0.1069	0.0673	0.0277	0.0277	0.0541	0.0541
B_2	0.1728	0	0.0937	0.0673	0.0409	0.1201	0.0277	0.0409	0.0277
B_3	0.1860	0.1332	0	0.0937	0.0409	0.1464	0.0277	0.1728	0.1332
B_4	0.1596	0.1464	0.0805	0	0.0805	0.0673	0.0277	0.0937	0.0805
B_5	0.1596	0.1464	0.0937	0.1201	0	0.1332	0.0409	0.0541	0.0673
B_6	0.0673	0.0673	0.0541	0.0673	0.0277	0	0.0937	0.0937	0.0277
B_7	0.1596	0.1728	0.1464	0.1464	0.1596	0.0937	0	0.0937	0.0277
B_8	0.1728	0.1728	0.1464	0.1069	0.1332	0.0937	0.0277	0	0.0277
B_9	0.1464	0.1728	0.1069	0.0277	0.0409	0.1069	0.0277	0.0277	0

Table 10 Total relation matrix (Ym)

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
B_1	0.3587	0.5024	0.4173	0.3120	0.2217	0.2654	0.1182	0.2488	0.2006
B_2	0.4406	0.2842	0.3100	0.2450	0.1733	0.2965	0.1078	0.2042	0.1490
B_3	0.6065	0.5545	0.3432	0.3582	0.2475	0.4201	0.1481	0.3961	0.2993
B_4	0.5033	0.4830	0.3521	0.2225	0.2408	0.2993	0.1228	0.2810	0.2216
B_5	0.5302	0.5084	0.3823	0.3495	0.1786	0.3748	0.1459	0.2670	0.2229
B_6	0.3293	0.3219	0.2555	0.2305	0.1586	0.1728	0.1580	0.2336	0.1333
B_7	0.6382	0.6314	0.5057	0.4414	0.3746	0.4118	0.1318	0.3604	0.2329
B_8	0.5851	0.5696	0.4583	0.3659	0.3175	0.3703	0.1426	0.2394	0.2079
B_9	0.4447	0.4566	0.3376	0.2215	0.1799	0.3056	0.1133	0.2021	0.1288

the best-worst method for ranking and the fuzzy DEMATEL method, lack of knowledge and expertise (B1) received the highest weight 0.3146 (α 1) followed by high capital investment (0.191, i.e., α 3) and stable environment (0.127. i.e., α 2) while limited option of crops to be produced (B9) has the lowest weight (0.0273, i.e., α 9). If these factors, especially the first three, are considered while planning and implementation of aquaponics, it has a great potential. The present research highlights the nine major challenges that any new entrant in the field has to address according to their importance in order to set up the aquaponics unit efficiently. Managers of allied businesses can use the proposed rankings and categorizations to evaluate the correct plan of action before incurring unnecessary costs to establish the unit. Thus, the obtained results not only address the concerns of the start-ups and corporations who want to adopt aquaponics, but they also in-turn increase the total investment and number of investors, who are interested to adopt this technology, by making it easier to enter the field. The outcomes can be used as a guideline to systematically tackle and eliminate all challenges as obstacles involved in setting up an aquaponics unit. This will help in extensive reduction of capital requirements and of negative environmental impacts.

The challenges faced in the implementation of aquaponics are gaining much attention as the importance of aquaponic

Fig. 2 Causal diagram

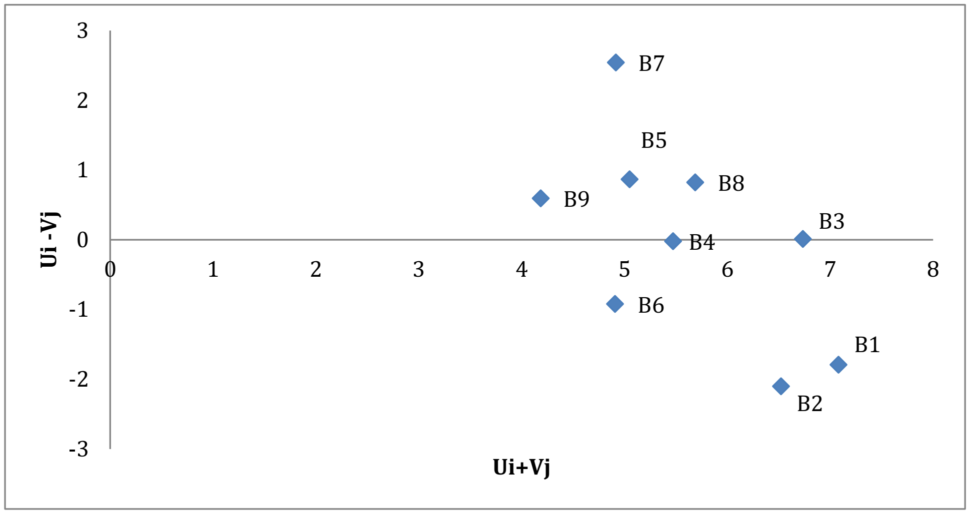

Table 11 The degree of central role

	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
U_i	2.6451	2.2107	3.3735	2.7265	2.9596	1.9936	3.7280	3.2564	2.3901
V_j	4.4366	4.3121	3.3620	2.7464	2.0925	2.9166	1.1885	2.4326	1.7963
$U_i + V_j$	7.0817	6.5228	6.7355	5.4729	5.0521	4.9102	4.9165	5.6890	4.1864
$U_i - V_j$	-1.7915	-2.1015	0.0115	-0.0199	0.8671	-0.9229	2.5395	0.8238	0.5938
Cause /effect group	Effect	Effect	Cause	Effect	Cause	Effect	Cause	Cause	Cause
Rank	8	9	5	6	2	7	1	3	4

technology is increasingly realized in the context of COVID-19 for the food security purpose and environmental point of view. Therefore, further research should also be done accommodating the sub-factors of the challenges identified in this research. Subsequently, local-weights for these sub-factors can be identified following the same fuzzy DEMATEL model. Overall, weights should be formed by including both parameters, i.e., weight of the parent challenge and weight of the sub-factor. Future research could also include the implementation frameworks to standardize the steps to be taken to tackle the ranked challenges. The research could further be focused on either reducing the time required to set up or be focused on capital required to set up the aquaponics unit.

Appendix 1. Experts profile

S. No.	Background	Designation	Experience	Location
1	Aquaponics Industry	Manager	8 years	National Capital Region
2	Aquaponics Industry	Owner	11Years	Kolkata
3	Academic	Professor (Botany)	15 Years	Bombay
4	Academic	Professor (Agriculture Science)	13 years	Chennai
5	Policy maker	Government official	12 years	Delhi
6	Policy maker	Government official	10 years	Bengaluru

Appendix 2. Questionnaire for best-worst method

Rank the most important barriers of aquaponics adoption as compared to others; assign a number from 1 to 9 to show the preference of a criterion over the others (Tables 12, 13, 14, 15, 16, 17, 18, 19, and 20). Also, rank the lease important barriers of aquaponics adoption as compared to others, assign a number from 1 to 9 to show the preference of a criterion over the others (Tables 21, 22, 23, 24, 25, 26, 27, 28, and 29).

Table 12 Rank of the most important barrier in context to Lack of knowledge and expertise

Rank the most important barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
Lack of knowledge and expertise (B1)									

Table 13 Rank of the most important barrier in context to Absence of stable environment

Rank the most important Barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
Absence of Stable environment (B2)									

Table 14 Rank of the most important barrier in context to High capital requirements

Rank the most important Barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
High capital requirements (B3)									

Table 15 Rank of the most important barrier in context to Nutrient limitation in fish excreta

Rank the most important Barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
Nutrient limitation in fish excreta (B4)									

Table 16 Rank of the most important barrier in context to Maintaining pH

Rank the most important Barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
Maintaining pH (B5)									

Table 17 Rank of the most important barrier in context to Poor pest and disease management

Rank the most important Barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
Poor pest and disease management (B6)									

Table 18 Rank of the most important Barrier in context to Interrupted power supply

Rank the most important Barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
Interrupted power supply (B7)									

Table 19 Rank of the most important Barrier in context to Limited plant and fish combinations

Rank the most important Barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
Limited plant and fish combinations (B8)									

Table 20 Rank of the most important barrier in context to Limited options of crops to be produced

Rank the most important Barriers	Lack of knowledge and expertise (B1)	Absence of Stable environment (B2)	High capital requirements (B3)	Nutrient limitation in fish excreta (B4)	Maintaining pH (B5)	Poor pest and disease management (B6)	Interrupted power supply (B7)	Limited plant and fish combinations (B8)	Limited options of crops to be produced (B9)
Limited options of crops to be produced (B9)									

Table 21 Rank of the least important barrier in context to Lack of knowledge and expertise

Rank the least important barriers	Lack of knowledge and expertise (B1)
Lack of knowledge and expertise (B1)	
Absence of Stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Table 22 Rank of the least important Barrier in context to Absence of stable environment

Rank the least important barriers	Absence of stable environment (B2)
Lack of knowledge and expertise (B1)	
Absence of Stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Table 23 Rank of the least important barrier in context to High capital requirements

Rank the least important barriers	High capital requirements (B3)
Lack of knowledge and expertise (B1)	
Absence of stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Table 24 Rank of the least important barrier in context to Nutrient limitation in fish excreta

Rank the least important barriers	Nutrient limitation in fish excreta (B4)
Lack of knowledge and expertise (B1)	
Absence of stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Table 25 Rank of the least important Barrier in context to Maintaining pH

Rank the least important barriers	Maintaining pH (B5)
Lack of knowledge and expertise (B1)	
Absence of Stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Table 26 Rank of the least important barrier in context to Poor pest and disease management

Rank the least important barriers	Poor pest and disease management (B6)
Lack of knowledge and expertise (B1)	
Absence of Stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Table 27 Rank of the least important barrier in context to Interrupted power supply

Rank the least important barriers	Interrupted power supply (B7)
Lack of knowledge and expertise (B1)	
Absence of Stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Table 28 Rank of the least important barrier in context to Limited plant and fish combinations

Rank the least important barriers	Limited plant and fish combinations (B8)
Lack of knowledge and expertise (B1)	
Absence of Stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Table 29 Rank of the least important barrier in context to Limited options of crops to be produced

Rank the least important barriers	Limited options of crops to be produced (B9)
Lack of knowledge and expertise (B1)	
Absence of Stable environment (B2)	
High capital requirements (B3)	
Nutrient limitation in fish excreta (B4)	
Maintaining pH (B5)	
Poor pest and disease management (B6)	
Interrupted power supply (B7)	
Limited plant and fish combinations (B8)	
Limited options of crops to be produced (B9)	

Appendix 3. Questionnaire for fuzzy DEMATEL method

Table 30 and 31 present the barriers and scale on which the experts are supposed to rank. Table 32 represents the questionnaire utilized for conducting the DEMATEL study. Each expert was asked to evaluate the impact of one indicator over the other indicators using an integer scale (from 0 to 4). Table 31 shows that if Indicator (i) has a weak direct influence on indicator (j), then a score of "1" is given to represent this weak influence. Conversely, if the indicator (i) has a strong direct influence on the indicator (j) then, a score of "3" is assigned and so on. A high score represents the belief of a higher influence of indicator (i) over indicator (j). The detailed scale is shown in Table 31.

Table 30 Barriers of aquaponics adoption

Symbol	Name of barrier
B1	Lack of knowledge and expertise
B2	Absence of Stable environment
B3	High capital requirements
B4	Nutrient limitation in fish excreta
B5	Maintaining pH
B6	Poor pest and disease management
B7	Interrupted power supply
B8	Limited plant and fish combinations
B9	Limited options of crops to be produced

Table 31 Linguistic terms and corresponding fuzzy numbers

Linguistic terms	Influence score	Triangular fuzzy numbers
No influence	0	0, 0.1, 0.25
Low influence	1	0.1, 0.25, 0.5
Moderate influence	2	0.25, 0.5, 0.6
High influence	3	0.5, 0.6, 0.75
Very high influence	4	0.6, 0.75, 1

Table 32 Barriers of aquaponics adoption and symbol

Indicators (j) Indicators (i)	B1	B2	B3	B4	B5	B6	B7	B8	B9
B1	0.00								
B2		0.00							
B3			0.00						
B4				0.00					
B5					0.00				
B6						0.00			
B7							0.00		
B8								0.00	
B9									0.00

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