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A Multi-Criteria decision framework for sustainable rainwater harvesting site selection based on livelihood Capital factors

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ABSTRACT

Water scarcity is intensifying globally, increasing the need for sustainable and locally adaptable water solutions. Rainwater harvesting systems (RHS) are promoted as a practical response, yet poor site selection often limits success. This study integrates the Sustainable Livelihood Framework (SLF) into the RHS site selection to assess how social, economic, and technical factors interact. A hybrid multi-criteria decision-making approach was applied, combining the Fuzzy Delphi Method to validate determinants, the Fuzzy Analytic Hierarchy Process to prioritize them, and Fuzzy DEMATEL to map interdependencies. Out of 43 initial determinants, 26 were validated. Results indicate that socio-economic livelihood capitals are the most influential, while natural factors like rainfall remain indispensable enabling conditions. Key determinants include rainfall, leadership support, community participation, water equity, and subsidies, whereas education, credit access, technical skills, energy supply, and maintenance costs drive implementation. The study offers a holistic framework for inclusive, resilient, and context-responsive water resource planning.

1. Introduction

Water scarcity is a growing global crisis, threatening human health, food security, and economic development. By 2030, global water demand is expected to exceed supply by 40% and by 2050, as many as 5.7 billion people will experience water stress [1–3]. These underscore the urgent need for sustainable, decentralized, and context-appropriate water solutions. Rainwater harvesting systems (RHS) offer a promising solution by capturing and storing rainfall for domestic, agricultural, and environmental use [4–6]. However, many RHS initiatives have underperformed, not due to flaws in technical design, but because of poor site selection driven [7,8]. Most existing site selection studies rely on GIS-based or multi-criteria ranking that treat determinants as independent variables, offering limited insight into how socio-economic and technical factors interact. Existing studies often prioritize physical parameters, while neglecting essential non-technical factors such as livelihood dimensions [9,10]. Thus, a critical gap remains in understanding how livelihood dimensions not only influence, but interact and exert causal effects on RHS site selection outcomes. The study seeks to develop a holistic site selection and planning framework that reflects both technical and non-technical determinants. By moving beyond engineering-centered models, this study aims to inform more inclusive, resilient, and sustainable water management strategies.

Prior studies highlighting the determinants affecting the RHS site selection often focus on technical and environmental variables [4,5,11]. Relying on these determinants alone overlooks number of important factors which can determine the long-term success [8,9,12]. For instance, the ability of local communities to manage systems depends on their skills, education, and health influence operational sustainability [10,13,14]. Community cooperation, trust, and local leadership also shape whether projects are effectively utilized [15–17]. The presence or absence of basic infrastructure such as roads, storage tanks, and maintenance tools significantly affect the feasibility of implementation [6,7,18]. Despite these studies several determinants shaping site selection, few studies have systematically examined how these determinants interact to determine long-term performance [10,18,19]. Existing studies often remain descriptive, fragmented, or narrowly focused on engineering-centered criteria [9,12,20]. Thus, this study adopts a Sustainable Livelihood Framework (SLF) to consider both technical and non-technical interdependencies. The study aims to answer the following questions:

RQ1: What are the key sustainable livelihoods determinants that

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influence the success of RHS site selection?

RQ2: What is the relative importance of the identified determinants in the RHS site selection success?

RQ3: How do the identified determinants influence one another within the socio-technical system of RHS site selection?

RQ4: How can the integration of livelihood and technical dimensions in a multi-criteria decision framework enhance inclusive and sustainable RHS site selection?

This study employed a hybrid multicriteria decision making (MCDM) approaches, namely, the Fuzzy Delphi Method (FDM), Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL). Recent studies highlight the growing application of MCDM approaches in sustainability planning in contexts that share structural similarities with water-stressed and resource-constrained regions [59,60]. FDM was applied to validate the most relevant determinants through expert consensus, ensuring that both technical and socio-economic dimensions were contextually appropriate [21,22]. FAHP was then used to prioritize these determinants by incorporating expert judgments with the capacity to handle uncertainty and vagueness inherent in complex decision-making [23]. FDEMATEL method is then used to uncover the causal and interdependent relationships among the determinants [21–23]. Together, these three fuzzy-based techniques MCDMs enable the development of a holistic decision-making framework that captures expert consensus, prioritizes critical determinants, and models the dynamic interconnections shaping sustainable RHS site selection. Specifically, this study contributes by (i) embedding livelihood theory into RHS site selection, (ii) identifying the relative importance of social, human, financial, natural, and physical capitals, and (iii) revealing the causal pathways through which non-technical factors govern long-term system performance. The remainder of the paper is organized as follows: Section 2 provides the relevant literature on SLF, RHS, and site selection factors. Section 3 outlines the case background and research methodology. Section 4 presents the findings. Section 5 discusses the results in relation to existing studies and practical challenges. Finally, Section 6 concludes with recommendations for policy, planning, and future research.

2. Literature review

2.1. Theoretical framework

This study is grounded in the SLF which offers a holistic understanding on how people utilize multiple forms of capitals to sustain their livelihoods [13,24]. SLF's multidimensional lens makes it relevant for understanding the non-technical determinants of RHS site selection success. This study assumes that the long-term sustainability of RHS is influenced not only by environmental suitability but also by local capacity, social cohesion, and institutional support [12,14,17]. Prior research supports SLF's applicability to water management. For instance, Kuruppu [13] applied the SLF to explore how cultural values influence water adaptation strategies, highlighting the importance of integrating relational and non-material assets into water management planning. Nasrnia and Ashktorab [25] used SLF to assess the drought resilience patterns of rural households. Rajab-Kalantarzadeh and Savari [26] used the SLF to explore how resilience impacts food security among rural households during droughts. Existing studies have suggested that future research should adopt multidimensional approaches capable of capturing the livelihood assets influencing climate adaptation [27]. This study adopts the SLF to guide a holistic approach to RHS site selection, recognizing that technical suitability alone does not guarantee long-term success.

2.2. Rainwater harvesting system

Water scarcity is a growing challenge across diverse regions of the world, driven by climate variability, population growth, and increasing pressure on existing water infrastructure. In arid and semi-arid regions of Africa and the Middle East, erratic rainfall and limited groundwater availability have intensified reliance on decentralized water solutions such as rainwater harvesting systems [23,25]. Similarly, parts of South Asia and Southeast Asia face seasonal water stress due to monsoon variability, rapid urbanization, and inadequate storage capacity, making RHS a critical adaptation strategy [20,34]. In Latin America, increasing climate extremes and unequal access to centralized water services have further highlighted the role of RHS in enhancing water security, resilience, and livelihood sustainability [14,61]. RHS is an important component of water management, particularly in those regions facing growing water stress, erratic rainfall, and rapid urbanization [4,5,11]. RHS reduces dependence on centralized water supply systems by utilizing locally available rainwater and enhancing resilience [7,9,18]. RHS also stores surface runoff and supplies non-potable water which can significantly lower water bills and infrastructure stress. Due to these benefits, there is an increasing interest in improving site selection practices to ensure RHS effectiveness and sustainability [28,29]. Hassan et al. [29] emphasize that even well-designed systems fail without suitable environmental and social conditions. Nevertheless, RHS implementation often falls short due to a poor site selection driven by overlooking crucial social and economic factors [3,30,31].

Recognizing the limitations of purely technical approaches, several recent studies have attempted to incorporate non-technical factors into RHS site selection models. Toosi et al. [32] integrated socio-economic variables such as proximity to infrastructure and natural features to enhance site suitability analysis. Hasan et al. [3] employed a multi-layered approach combining technical and socio-economic factors to identify sites that optimize benefits. Abdalla et al. [5] considered a range of biophysical and socio-economic factors, including rainfall, land cover, slope, drainage density, and distance to roads and streams. Suprapti et al. [8] emphasized the importance of engaging multiple stakeholders and integrating both environmental and community-related dimensions. Although existing studies incorporate socio-economic and community-related criteria into RHS site selection, the broader livelihood dimensions that shape long-term sustainability remain insufficiently addressed [33,34]. Most studies treat socio-economic factors as independent or static criteria, rather than as an interconnected system of livelihood assets with dynamic causal relationships. This gap limits the analytical depth and practical relevance of current site selection models, particularly in vulnerable and resource-constrained contexts. To address this limitation, this study adopts the SLF and integrates it with a hybrid FDM–FAHP–FDEMATEL approach to capture both the relative importance and causal interdependencies of livelihood and technical determinants, thereby strengthening the social legitimacy and operational sustainability of RHS interventions.

2.3. Sustainable livelihood dimensions

Natural capital (AS1) is often the most visible and prioritized factor in RHS planning, including rainfall availability, soil characteristics, topography, vegetation cover, and water runoff potential [30]. From a technical standpoint, selecting sites with sufficient and consistent rainfall, permeable soils, and appropriate slopes ensures better water capture [35–37]. it affects the environmental sustainability of the system, such as minimizing erosion or groundwater depletion [9,11,38]. However, a purely ecological focus may bypass dryland where water stress is most severe and livelihood vulnerability is highest [9,10,39]. Hence, while natural capital is essential for operational success, Pool et al. [40] highlights that its consideration must be balanced with equity, ensuring that the most disadvantaged regions are not overlooked merely due to biophysical limitations.

Human capital (AS2) refers to individual-level capacities including knowledge, skills, health, and labor and significantly influences a community's ability to operate RHS [7,13,41]. Puppala et al. [42] asserts that communities where individual members possess higher levels of knowledge and awareness demonstrate greater capacity to sustain RHS and adopt water-saving practices. However, favoring such areas in site selection risks excluding marginalized or low-capacity communities that may lack these advantages but still face acute water needs [37,41,43]. On the other hand, investing in areas with low human capital could generate long-term benefits by coupling RHS with education, training, and health improvements [10,15,44]. In this sense, RHS site selection should account for current capacities as well as the potential to build them over time.

Social capital (AS3) captures collective and relational attributes such as networks of trust, shared norms and institutional linkages that enable coordinated action within communities [2,45,46]. Communities with strong social capital are more likely to organize for system upkeep, share water equitably, and resolve conflicts constructively [16,24,40]. These qualities are essential where RHS serve multiple users or require coordinated operation. For instance, traditional water-sharing systems or village councils can provide a strong foundation for participatory management. However, in fragmented or politically divided communities, poor social cohesion may lead to exclusion, unequal access, or neglect of shared facilities [17,26,47]. Recognizing levels of social capital during site selection allows planners to either harness existing collaborative structures or identify where social facilitation efforts may be required to ensure inclusive participation and benefit-sharing.

2.4. Financial capital (AS4)

encompasses income, savings, access to credit, and remittance flows which affects a community's ability to contribute benefit from RHS [19,20,48]. Communities with better financial standing can invest in system upgrades and use harvested water for income-generating activities [1,49]. However, concentrating RHS efforts only in financially secure areas risks reinforcing inequality [20,31]. Conversely, targeting low-financial-capital areas may require external subsidies or revolving funds [50–52]. Site selection that considers financial capital therefore reflects both the current capacity for system sustainability and the potential for RHS to act as a catalyst for livelihood enhancement and poverty reduction [23,53,54].

Physical capital (AS5) refers to the infrastructure that supports livelihood strategies that can influence the viability of RHS [33,50,55]. Good road access reduces transportation costs for construction materials and maintenance personnel, while nearby water-related infrastructure can allow for system integration or scaling [27,56]. Areas with schools, health centers, or agricultural schemes also offer strategic value for community-wide impact. However, prioritizing physically well-equipped areas may deepen existing disparities, as remote or underserved communities continue to face neglect [55,57]. Therefore, physical capital should be viewed not just as a technical convenience but as a component offering both efficiencies and opportunities for inclusive progress.

2.5. Proposed Measures

This study identified 43 determinants from the literature (Table 1), which were categorized into the five dimensions of the SLF: human, social, natural, physical, and financial capital.

3. Methods

3.1. Case Study: Somaliland

Somaliland is in the Horn of Africa and is characterized by an arid to semi-arid climate, with average annual rainfall typically ranging between 200 and 400 mm, most of which is highly variable and concentrated within short rainy seasons. More than 60–70% of the population depends directly on rain-fed agriculture and livestock for their livelihoods, making water availability a critical determinant of socioeconomic stability. Recurrent droughts over the past decades have resulted in significant water stress, with rural communities often traveling 10–30 km to access water during dry seasons. Access to improved water sources remains limited, particularly in rural areas, where coverage is estimated to be below 50%, compared to higher but still constrained urban access. Groundwater resources are often deep, saline, or financially inaccessible, while centralized water infrastructure is insufficient to meet growing demand. In this context, RHS provide a vital decentralized solution, yet their sustainability depends strongly on social organization, financial capacity, and local skills, underscoring the need for a livelihood-based site selection framework in Somaliland.

Table 1
RHS Site Selection Determinants.

Aspects	Criteria		Reference
AS 1: Natural Capital	ID1	Rainfall	[4,5,9,11,12,34–38]
	ID2	Catchment Area	
	ID3	Land Slope	
	ID4	Soil Texture	
	ID5	LULC Pattern	
	ID6	Evapotranspiration Rates	
	ID7	Groundwater Table	
	ID8	Drainage Density	
	ID9	Curve Number	
	ID10	Elevation Range	
Human Capital	ID11	Technical Skills	[7,14,15,41–44]
	ID12	Community Awareness	
	ID13	Traditional knowledge	
	ID14	Education Level	
	ID15	Health Awareness	
	ID16	Gender roles	
	ID17	Labor Availability	
	ID18	Youth engagement	
Social Capital	ID19	Community Participation	[16,25,40,45–47]
	ID20	Experience	
	ID21	Trust in Institutions	
	ID22	Stakeholder Collaboration	
	ID23	Local Leadership Support	
	ID24	Conflict resolution	
	ID25	Social networks	
	ID26	Water Equity	
	ID27	Social Norms	
Financial Capital	ID28	Affordability Level	[19,20,49,51–54]
	ID29	Income Stability	
	ID30	income fluctuation	
	ID31	Access to Credit	
	ID32	External Subsidies	
	ID33	Microfinance Access	
	ID34	Maintenance Cost	
	ID35	Willingness to Pay	
Physical Capital	ID36	Infrastructure Access	[32,33,55–57]
	ID37	Construction Materials	
	ID38	Road Connectivity	
	ID39	Transport Availability	
	ID40	Energy Supply	
	ID41	Land Tenure Security	
	ID42	Site Accessibility	
	ID43	System Stability	

3.2. Data collection

This study employed a multi-stage data collection approach aligned with the hybrid Fuzzy Delphi–FAHP–FDEMATEL framework. In the first stage, a comprehensive review of previous studies on RHS and SLF factors was conducted to identify an initial set of potential site selection determinants. The selection of aspects and criteria was guided by the SLF, which defines five core livelihood capitals. These determinants formed the basis for expert evaluation in subsequent stages. Experts were selected using purposive sampling based on their professional involvement in water resource management, infrastructure planning, sustainability assessment, or related policy domains. Inclusion criteria required relevant professional experience and prior exposure to RHS projects or decision-making processes. Experts were contacted via institutional emails and professional networks, and participation was voluntary with informed consent. A total of 50 experts were invited to participate, of whom 39 completed the survey, resulting in a response rate of 78%. Table 2 shows experts by educational level, experience, and occupational affiliation (academia, government, and industry). Disciplinary backgrounds such as civil, environmental, and water engineering, as well as sustainability science, are represented across these groups, ensuring balanced technical, social, and economic coverage.

Data were collected using a structured questionnaire consisting of three sections corresponding to the applied methods. The first section FDM asked experts to evaluate the importance and relevance of the identified determinants using linguistic terms, with the aim of validating the most critical factors under uncertainty. The second section FAHP requested experts to perform pairwise comparisons among the validated determinants to assess their relative importance and priority. The third section FDEMATEL asked experts to assess the degree of influence among determinants, enabling the identification of causal and interdependent relationships within the system. The FDM questionnaire was administered using Google Forms, while the FAHP and FDEMATEL questionnaires were distributed using Excel-based survey sheets to facilitate structured pairwise and influence assessments. Prior to full deployment, the questionnaire was reviewed and validated by a subset of experts to ensure clarity, relevance, and consistency with the study objectives. This multi-stage and expert-driven data collection process ensured the reliability and contextual relevance of the input data used to develop the holistic RHS site selection framework. Fig. 1 illustrates the overall research flowchart and data collection sequence.

3.3. Data analysis

This section details the sequential steps of the data analysis methods applied in the study. All data analyses in this study were implemented using Microsoft Excel, employing customized spreadsheets to perform fuzzy aggregation, consistency analysis, defuzzification, and DEMATEL matrix computations.

3.3.1. FDM analytical steps

- *Converting linguistic terms:* Table 3 is used to convert the expert evaluation results into Triangular Fuzzy Numbers (TFNs).
- *Experts Consensus:* Eq. (1) is used to calculate the geometric mean of the fuzzy weight (w_j) of each criterion and aspect

$$w_j = \left\{ a_j = min(a_{ij}), b_j = (\sum_{i=1}^{n} (b_{ij}))^{1/n}, c_j = max(c_{ij}) \right\} \tag{1}$$

where *j* indicates criterion *j's* level of significance, *i* stands for the expert that rated the criterion, *n* refers to the number of interviewed experts, and *a*, *b*, and *c* indicate the values of the TFNs.

Table 2
Experts Profile.

	Characteristics	Frequency	Percentage
Education Level	PhD	6	21%
	Master's	12	41%
	Bachelor's	17	59%
	Other	4	14%
Experience	> 15 Years	13	33%
	5——10 Years	20	51%
	< 5 Years	6	15%
Occupation	Academics	14	36%
	Government	10	26%
	Industry	15	38%

- *Defuzzification:* Eq. (2) is used to defuzzify the aggregated fuzzy weights

$S_j = \frac{a_j+b_j+c_j}{3} j = 1,2,3.....m$ (2).where m is the total number of criteria considered.

- *Validating drivers:*

The last stage involves establishing a threshold (α) to determine the significance of criteria. The threshold value was determined based on the average of the defuzzified weights obtained from the FDM analysis. If $S_j \geq \alpha$, the criterion j^{th} is considered valid; if $S_j \leq \alpha$, the j^{th} criterion is insignificant and removed.

3.3.2. FAHP analytical steps

- *Construct Pairwise comparison:* The experts compare the aspects and criteria using linguistic terms and forming a square matrix. The scores are then transferred into their corresponding TFN's using the values in Table 4.
- *Compute the consistency analysis:* This is step ensures that the judgments of the experts are consistent and reliable, Eq. (3) is used to calculate Saaty's consistency index (CI) and Eq. (4) is used to calculate the consistency ratio (CR), where CR ≤ 0.1 was taken as the acceptable consistency cut off.

$$\mathrm{CI} = \frac{\lambda_{\max} - \mathrm{k}}{\mathrm{k} - 1} \tag{3}$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{4}$$

Where $\lambda_{\max}$ is average consistency measure, *k* is the size of the matrix and RI is the random index proposed by [58] given in Table 5.

- *Compute the aggregated fuzzy pairwise comparison matrix:* After the consistency of the expert's judgment are approved, the expert matrices are combine using Eq. (5).

$$\mathrm{l_{ij}} = \min(\mathrm{l_{ijk}}), \mathrm{m_{ij}} = (\sum_{\mathrm{k=1}}^{\mathrm{n}} (\mathrm{m_{ijk}}))^{1/n}, u_{ji} = \max(u_{ijk}) \tag{5}$$

Where (lijk, mijk, uijk) are the fuzzy evaluation of sample members k (k = 1,2, …,K) and (l_{ij}, m_{ij}, u_{ij}) are the judgments of the experts *k (1,2, …n).*

- *Calculate fuzzy synthetic extent*: Then Eq. (6) is used to calculate the value of the fuzzy synthetic extent with respect to the *i*-th object.

$$W = S_i = \sum_{j=1}^{m} M_{gi}^{j} * \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{6}$$

Where:

$\sum_{j=1}^{m} M_{gi}^{j}$ is the fuzzy addition operation of *m* extent analysis values for a particular matrix and Eq. (7) is applied to calculate it:

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_i, \sum_{j=1}^{m} m_i, \sum_{j=1}^{m} u_i \right) \tag{7}$$

$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1}$ is the fuzzy addition operation of M_{gi}^{j} ($j = 1, 2,...n$) and Eq. (8) and Eq. (9) is used:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{n} l_i, \sum_{j=1}^{n} m_i, \sum_{j=1}^{n} u_i \right) \tag{8}$$

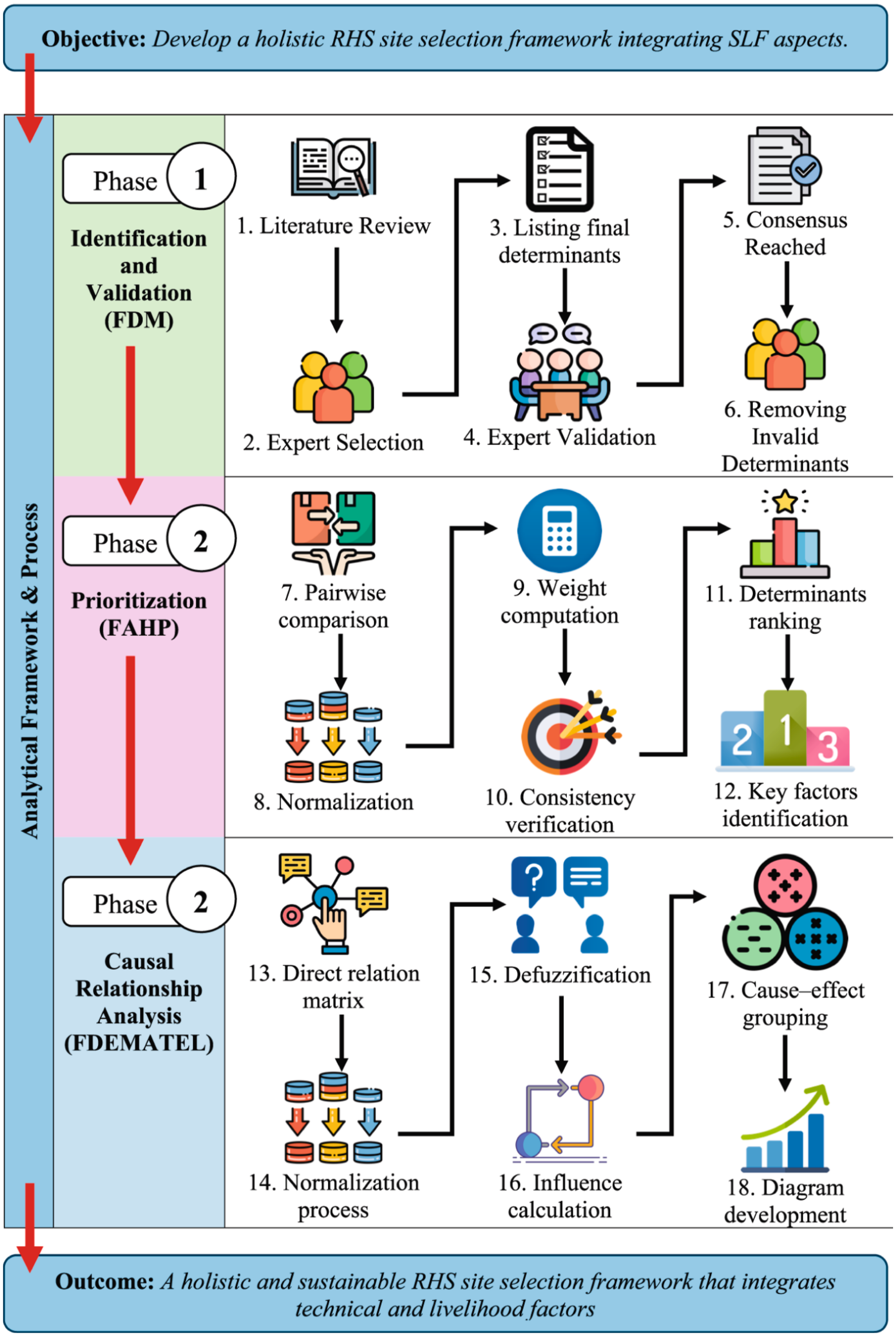

Fig. 1. Research flowchart.

Table 3
TFNs for FDM and FDEMATEL assessment.

Linguistic Terms	Corresponding TFNs		
Extreme	0.75	1.00	1.00
Demonstrated	0.50	0.75	1.00
Strong	0.25	0.50	0.75
Moderate	0.00	0.25	0.50
Equal	0.00	0.00	0.25

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{j=1}^{n} l_i}, \frac{1}{\sum_{j=1}^{n} m_i}, \frac{1}{\sum_{j=1}^{n} u_i}\right) \tag{9}$$

Table 4
FAHP rating scale.

Linguistic terms	Level of Influence	TFN's
Equal important	1	(1, 1, 1)
Somewhat more important	3	(2, 3, 4)
Much more important	5	(4, 5, 6)
Very much more important	7	(6, 7, 8)
Absolutely more important	9	(8, 9, 9)
Intermediate values	2	(1, 2, 3)
	4	(3, 4, 5)
	6	(5, 6, 7)
	8	(7, 8, 9)

Table 5
Random index values.

k	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

- *Determine the degree of possibility using Eq. (10)*: $M_2 = (l_2, m_2, u_2,) \geq M_1 = (l_1, m_1, u_1,)$ is defined as:

$$V(M_2 \geq M_1) = \sup_{y \geq x}[\min(u_{M1}(x), u_{M2}(y)\ )] \tag{10}$$

The membership degree of possibility can be identified from Eq. (11):

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2\ ) = u_{M2}(d) \tag{11}$$

$$u_{M2}(d) = \begin{cases} 1, if\boldsymbol{m}_2 \geq \boldsymbol{m}_1 \\ 0, if\boldsymbol{l}_1 \geq \boldsymbol{u}_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, Otherwise \end{cases}$$

To compare M_1 and M_2, both the values of $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$ are needed.

- *Determine the weight vector:* The degree of possibility for a convex fuzzy number to be greater than *k* convex fuzzy numbers M_i *(i = 1, 2, …k)* is defined by Eq. (12):

$$V(M \geq M_1, M_1, \cdots M_k\ ) = \min V(M \geq M_{i1}) \tag{12}$$

Where i = 1, 2,…k. Assume that:
$\acute{d}(C_i) = \min V\ (S_i \geq S_k)$ (13).
For *k = 1,2,….n; k ≠ i.* Then the weight vector is given by:
$\acute{W} = (\acute{d}(C_1), \acute{d}(C_2), \ldots\ldots \acute{d}(C_n))^T$ (14).
Where C_i *(i = 1,2, …n)* are *n* elements.

- *Normalization:* the normalized weight vectors are calculated by applying Eq. 15:

  $W = (d(C_1), d(C_2), \ldots\ldots d(C_n))^T$ (15).

- *Global Weights:* Calculate the global weight of each factor (criteria) by multiplying the weight of the factor to aspect weight and the number of criteria in that aspect.

3.3.3. FDEMATEL analytical steps

- *Converting linguistic terms:* Expert evaluations in the FDEMATEL questionnaire undergo conversion into TFNs using Table 2.
- *Normalizing TFNs:* The TFNs are normalized to ensure comparability among different criteria using Eq.16.

$$S = \left(s\widetilde{z}^f_{lij}, s\widetilde{z}^f_{mij}, s\widetilde{z}^f_{uij}\right) = \left[\frac{\left(z^f_{lij} - minz^f_{lij}\right)}{\left(maxz^f_{uij} - minz^f_{lij}\right)}, \frac{\left(z^f_{mij} - minz^f_{mij}\right)}{\left(maxz^f_{uij} - minz^f_{lij}\right)}, \frac{\left(z^f_{uij} - minz^f_{mij}\right)}{\left(maxz^f_{uij} - minz^f_{lij}\right)}\right] \tag{16}$$

where $(s\widetilde{z}^f_{lij}, s\widetilde{z}^f_{mij}, s\widetilde{z}^f_{uij})$ represents the normalized values of a TFN.

- *Computing normalized crisp values:* Left (S^f_{ltij}) and right (S^f_{rtij}) normalized values, total normalized crisp values, and crisp values were calculated using Eq. (17), Eq. (18), and Eq. (19), respectively.

$$\left(S^f_{ltij}, S^f_{rtij}\right) = \left[\frac{s\widetilde{z}^f_{mij}}{\left(1 + s\widetilde{z}^f_{mij} - s\widetilde{z}^f_{lij}\right)}, \frac{s\widetilde{z}^f_{uij}}{\left(1 + s\widetilde{z}^f_{uij} - s\widetilde{z}^f_{mij}\right)}\right] \tag{17}$$

$$S^f_{ij} = \left[\frac{S^f_{ltij}\left(1 - S^f_{ltij}\right) + \left(S^f_{rtij}\right)^2}{\left(1 - S^f_{ltij} + S^f_{rtij}\right)}\right] \tag{18}$$

$$\widetilde{w}^f_{ij} = min\widetilde{z}^f_{lij} + S^f_{ij}\left(maxz^f_{uij} - minz^f_{lij}\right) \tag{19}$$

- *Calculating synthetic value:* The synthetic value is obtained by averaging the opinions experts using Eq. (20), this gives an initial direct relation matrix (IDRM) that sums the opinions of n experts.

$$w^f_{ij} = \frac{1}{n}\left(\widetilde{w}^1_{ij} + \widetilde{w}^2_{ij} + \widetilde{w}^3_{ij} + \cdots + \widetilde{w}^f_{ij}\right) \tag{20}$$

  where w_{ij} denotes the degree to which criterion *i* affects criterion *j*.

- *Normalized direct relationship matrix (U):* U value is obtained by standardizing the IDRM and applying Eq. (21).

$$U = w \otimes IDMR \tag{21}$$

  where $w = max\left(\sum_{j=1}^n w^f_{ij}\right)$ for all *i* from 1 to *n*.

- *Total interrelationship matrix Y:* The total interrelationship matrix is computed using Eq. (22) to capture the broader influence dynamics.

$$Y = U(I - U)^{-1} \tag{22}$$

  where *I* represent an identity matrix of size n.

- *Establishing causal relationship:* Lastly, factors are classified into causal and effect groups by utilizing Eq. (23) and Eq. (24)

  $D = \sum_{j=1}^n U_{ij}$ for all *j* from 1 to *n* (23).
  $R = \sum_{i=1}^n U_{ij}$ for all *i* from 1 to *n* (24).

Vector D represents the total sum of values across all rows, while vector R corresponds to the sum of values across all columns. The horizontal axis, known as the prominence axis, is derived by adding D and R together. In contrast, the vertical axis, referred to as the relation axis, is determined by the difference between D and R. If D − R is positive, the factor belongs to the causal group, indicating it plays an influential role. Conversely, a negative D − R value signifies that the factor falls within the effect group, meaning it is primarily influenced by other factors.

4. Results and Discussion

4.1. Validating determinants

This study adopted the FDM to validate the determinants of RHS site selection success. An initial set of 43 determinants (ID1 – ID43) was gathered from the literature review. Using the FDM, the study applied an acceptance threshold based on an average weight of 0.640. Determinants scoring above this threshold were considered valid and retained for further analysis. Table 6 presents the validated determinants, renumbered (D1 – D26). This validation step ensures that RHS site selection decisions are grounded in determinants with strong

Table 6
Renaming Accepted Determinants.

Aspect	Criteria	
AS1: Natural Capital	D1	Soil Texture
	D2	LULC Pattern
	D3	Curve Number
	D4	Rainfall
	D5	Drainage Density
	D6	Land Slope
	D7	Elevation Range
AS2: Human Capital	D8	Technical Skills
	D9	Community Awareness
	D10	Education Level
	D11	Labor Availability
AS3: Social Capital	D12	Community Participation
	D13	Trust in Institutions
	D14	Local Leadership Support
	D15	Water Equity
	D16	Social Norms
AS4: Financial Capital	D17	Affordability Level
	D18	income fluctuation
	D19	Access to Credit
	D20	External Subsidies
	D21	Maintenance Cost
AS5: Physical Capital	D22	Infrastructure Access
	D23	Construction Materials
	D24	Energy Supply
	D25	Land Tenure Security
	D26	System Stability

Table 7
Aspects and Determinants Rankings.

Aspect	Ranking	Determinants		Weights	Ranking
AS1: Natural Capital	5	D1	Soil Texture	0.191	19
		D2	LULC Pattern	0.120	26
		D3	Curve Number	0.187	21
		D4	Rainfall	0.256	1
		D5	Drainage Density	0.204	11
		D6	Land Slope	0.187	20
		D7	Elevation Range	0.123	25
AS2: Human Capital	2	D8	Technical Skills	0.212	9
		D9	Community Awareness	0.185	22
		D10	Education Level	0.210	10
		D11	Labor Availability	0.202	12
AS3: Social Capital	1	D12	Community Participation	0.229	3
		D13	Trust in Institutions	0.213	8
		D14	Local Leadership Support	0.232	2
		D15	Water Equity	0.224	4
		D16	Social Norms	0.202	13
AS4: Financial Capital	3	D17	Affordability Level	0.219	6
		D18	income fluctuation	0.172	23
		D19	Access to Credit	0.216	7
		D20	External Subsidies	0.223	5
		D21	Maintenance Cost	0.165	24
AS5: Physical Capital	4	D22	Infrastructure Access	0.192	18
		D23	Construction Materials	0.200	16
		D24	Energy Supply	0.202	14
		D25	Land Tenure Security	0.195	17
		D26	System Stability	0.201	15

expert consensus, reducing uncertainty and improving the relevance of subsequent analyses. By filtering out weakly supported factors, the framework enhances decision focus and practical applicability in real-world planning contexts.

4.2. *Prioritizing determinants*

Expert judgments were initially collected using linguistic terms and aggregated to reflect collective opinions, with consistency confirmed as acceptable (CR $\leq$ 0.1). The fuzzy synthetic extent values for all determinants were derived, and their corresponding weights were calculated (Table 7). The FAHP results show that among the five aspects of the SLF, social capital had the highest priority (0.220), followed by human capital (0.202) and financial capital (0.199). Fig. 2 illustrates the relative weights of the aspects expressed as percentages, reflecting their comparative weight in the overall hierarchy. For specific determinants, the top five were rainfall (1), local leadership support (2), community participation (0.229), water equity (0.224), and external subsidies (0.223), highlighting the most significant factors in RHS site selection. Table 7 presents the rankings of both the main aspects and their corresponding determinants. These prioritization results directly inform the initial problem of ineffective RHS implementation by identifying the conditions under which RHS interventions are most likely to succeed. The dominance of social and human capital factors indicates that technical suitability alone is insufficient; instead, community readiness, leadership support, and equitable access are decisive in determining system uptake and longevity. For practitioners, this implies that site selection decisions should be accompanied by parallel investments in social engagement and institutional capacity rather than relying solely on biophysical indicators.

4.3. *Assessing interrelationship*

The results of the FDEMATEL analysis provide critical insights into the causal interrelationships among the SLF aspects and the key determinants. The causal interrelationships among aspects and barriers are identified by computing the total interrelationship matrix, as in Table 8 and Table 9. Among the five SLF aspects, *Social Capital and Financial Capital* emerged as the core aspects, exerting both strong influence and high dependence, indicating their central role in balancing technical feasibility with community and economic resilience. *Natural Capital and Physical Capital* were identified as the driving aspects, serving as the foundational enablers that initiate and propagate influence across the system, while *Human Capital* appeared as the effect group, primarily shaped by the dynamics of the other livelihood capitals. As shown in Fig. 3, these relationships illustrate the systemic nature of RHS site selection, where socio-economic and environmental factors are deeply interconnected. At the determinant level, eight factors were found to have the highest influence and importance: *Education Level (D10), Access to Credit (D19), Technical Skills (D8), Energy Supply (D24), Local Leadership Support (D14), Maintenance Cost (D21), Rainfall (D4), and External Subsidies (D20)*. These determinants, visualized in Fig. 4, represent the core drivers that shape sustainable RHS planning, integrating livelihood resilience with infrastructural and environmental suitability. The cause–effect structure provides actionable guidance for addressing the root causes of RHS underperformance rather than its symptoms. By identifying education level, access to credit, technical skills, and leadership support as key driving determinants, the analysis highlights leverage points where targeted interventions can trigger cascading improvements across the system. This enables decision-makers to prioritize capacity-building and financial mechanisms that enhance long-term system sustainability, rather than focusing exclusively on site-level engineering adjustments.

5. Implications

5.1. *Theoretical Implications*

The integration of prioritization and cause–effect analyses in this study offers a significant theoretical contribution by clarifying how livelihood dimensions interact to shape RHS site selection beyond technical or economic optimization. The prioritization results indicate that social, human, and financial capitals exert the strongest overall

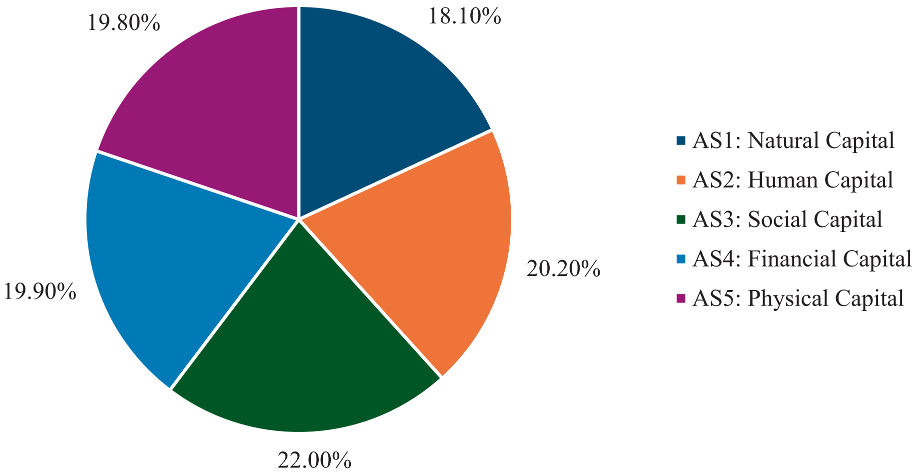

Fig. 2. Aspects Weights.

Table 8
Determinants Cause-Effect Weights.

Aspects	D	R	D + R (Prominence)	D-R (Relationship)
AS1: *Natural Capital*	1.399	1.219	2.618	0.180
AS2: *Human Capital*	1.299	1.499	2.798	−0.200
AS3: *Social Capital*	2.043	1.866	3.909	0.177
AS4: *Financial Capital*	1.943	1.654	3.597	0.289
AS5: *Physical Capital*	1.582	1.498	3.080	0.084

influence on RHS site selection success. This finding advance existing RHS literature, which has largely emphasized natural, physical, and economic efficiency parameters as the primary determinants of feasibility [7,9,12]. For instance, recent studies employing machine learning, regression modeling, and economic simulation approaches demonstrated the importance of rainfall, water tariffs, roof area, and catchment fraction in predicting the financial performance of RHS [62,63]. While these studies provide tools for forecasting economic viability and optimizing system design, they typically assume that social organization, institutional capacity, and financial access are either stable or externally managed. In contrast, this study shows that social and financial capitals are not merely contextual conditions but causal mechanisms that regulate whether technical and economic potential can be translated into sustained system operation.

Theoretically, this study refines prior economic and performance-oriented frameworks by revealing the dual role of social and financial capitals as both enabling and governing forces. Social capital emerges as the connective structure linking technical design with collective action, institutional trust, and equitable resource sharing. Financial capital, meanwhile, functions as the stabilizing backbone that supports maintenance, affordability, and long-term system continuity. Unlike earlier studies that identify low awareness or high costs as adoption barriers [63], this research embeds these challenges within a broader livelihood system, demonstrating how deficits in social cohesion or financial capacity amplify technical and economic risks. Overall, the theoretical contribution of this study lies in redefining sustainable water resource management as a socio-technical process embedded in a dynamic livelihood system. Rather than replacing biophysical or economic analyses, the SLF-based framework complements them by explaining why technically viable and economically attractive RHS projects succeed in some contexts but fail in others.

Table 9
Determinants Cause-Effect Weights.

No.	Determinants	D	R	D + R (Prominence)	D-R (Relationship)
D1	Soil Texture	2.543	2.575	5.118	−0.032
D2	LULC Pattern	2.399	2.599	4.998	−0.200
D3	Curve Number	2.243	2.566	4.809	−0.323
D4	Rainfall	2.311	2.293	4.604	0.018
D5	Drainage Density	1.982	1.782	3.764	0.200
D6	Land Slope	2.053	2.003	4.056	0.050
D7	Elevation Range	1.812	1.899	3.711	−0.087
D8	Technical Skills	2.531	2.423	4.954	0.108
D9	Community Awareness	2.085	2.023	4.108	0.062
D10	Education Level	2.631	2.423	5.054	0.208
D11	Labor Availability	2.143	2.191	4.334	−0.048
D12	Community Participation	1.989	2.011	4.000	−0.022
D13	Trust in Institutions	2.003	1.991	3.994	0.012
D14	Local Leadership Support	2.499	2.413	4.912	0.086
D15	Water Equity	2.043	1.888	3.931	0.155
D16	Social Norms	2.123	2.201	4.324	−0.078
D17	Affordability Level	2.543	2.545	5.088	−0.002
D18	Income flactuation	2.499	2.587	5.086	−0.088
D19	Access to Credit	2.594	2.311	4.905	0.283
D20	External Subsidies	2.322	2.256	4.578	0.066
D21	Maintenance Cost	2.441	2.410	4.851	0.031
D22	Infrastructure Access	1.768	2.123	3.891	−0.355
D23	Construction Materials	1.875	2.111	3.986	−0.236
D24	Energy Supply	2.533	2.311	4.844	0.222
D25	Land Tenure Security	1.880	2.065	3.945	−0.185
D26	System Stability	1.901	2.198	4.099	−0.297

5.2. *Managerial Implications*

The prioritization and cause–effect analyses provide a comprehensive view of how technical and livelihood determinants collectively shape the success of RHS site selection. The prioritization results highlight key determinants such as rainfall, local leadership support, community participation, water equity, and external subsidies as the most critical conditions for effective system performance. These determinants define where and under what conditions RHS projects are most likely to thrive. In contrast, the cause–effect analysis reveals that factors like

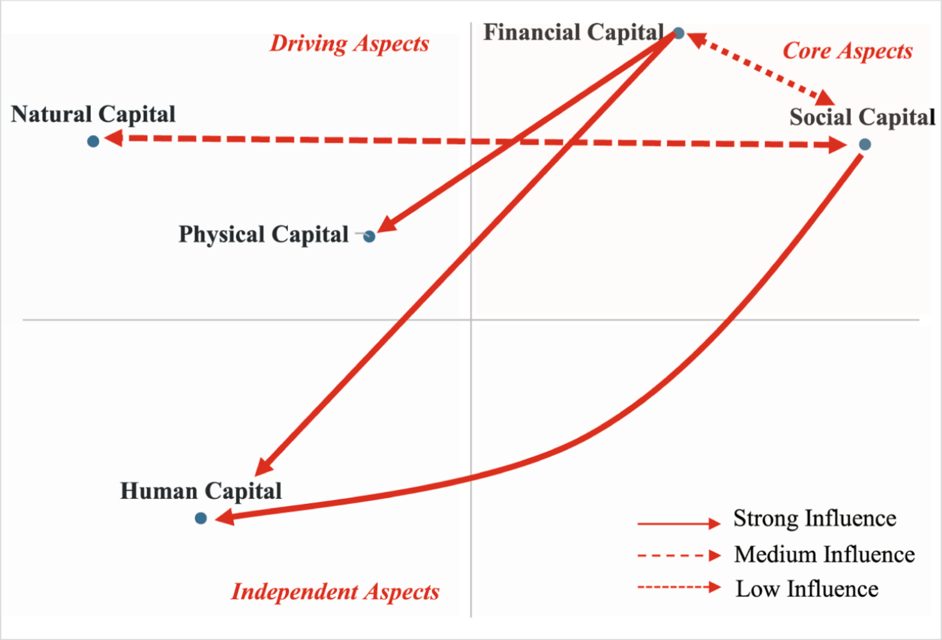

Fig. 3. SLF Aspects Cause-Effect Diagram.

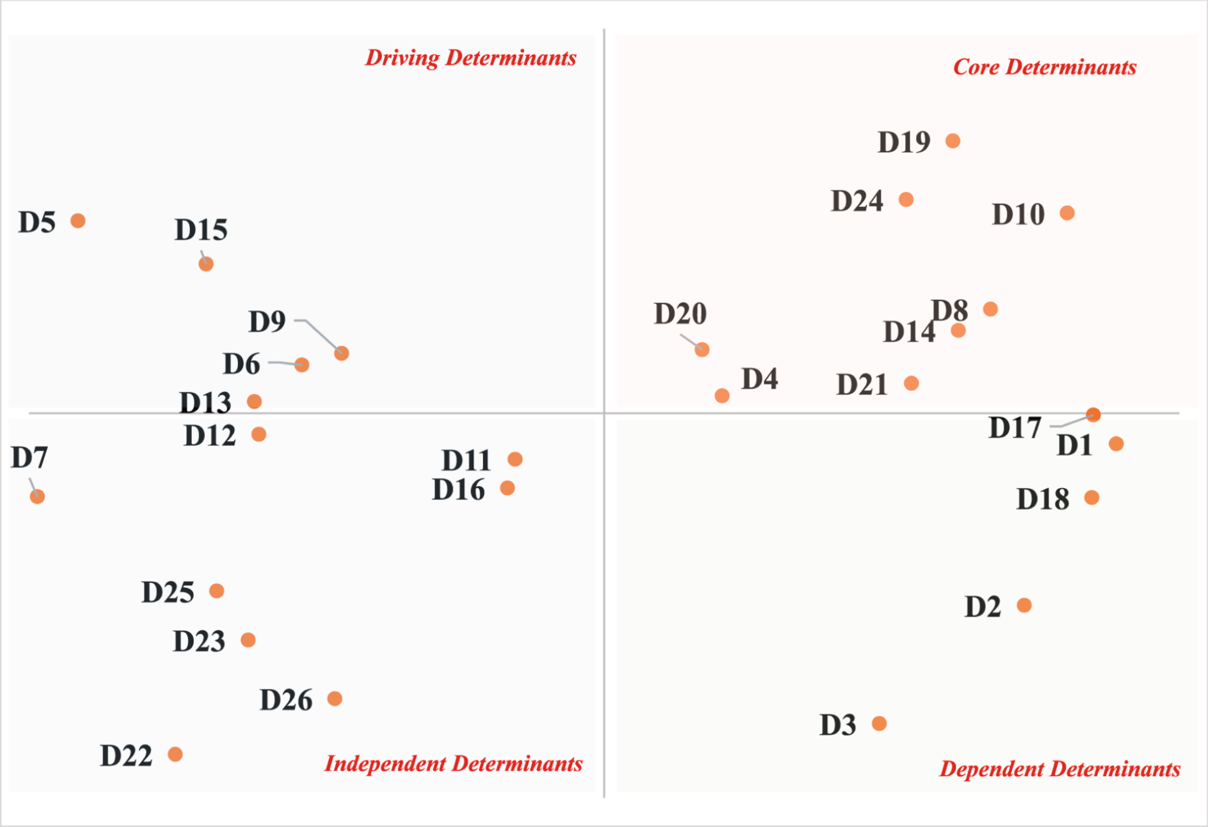

Fig. 4. Determinants Cause-Effect Diagram.

education level, access to credit, technical skills, energy reliability, leadership capacity, and maintenance cost act as underlying drivers that influence the performance of the entire system. This implies that sustainable RHS implementation requires not only identifying suitable sites but also building the human, institutional, and economic capacities that sustain those sites over time.

Practically, these findings suggest that policy-makers and project managers should adopt a two-tier strategy for RHS development. First, focus on environmental suitability and social inclusion by prioritizing areas with adequate rainfall, fair water distribution, and strong local governance structures. These conditions ensure that the technical system aligns with environmental and social realities. Second, strengthen systemic enablers that enhance the community's ability to manage and maintain the systems effectively. Local leadership should be empowered to coordinate stakeholder engagement, while financial programs can reduce the economic barriers to participation. Furthermore, maintenance cost and energy reliability should be integrated into early design and planning stages to prevent system failures. Overall, the combined insights from the prioritization and cause–effect analyses imply that sustainable RHS site selection depends on the alignment of physical feasibility with social capability and financial empowerment. Long-term success, therefore, lies in designing interventions that merge environmental suitability with human and institutional resilience, transforming rainwater harvesting from a technical intervention into a sustainable livelihood strategy.

To operationalize these insights in practice, the derived FAHP weights can be used to construct a composite suitability scoring system for candidate sites, where each determinant is normalized and weighted according to its relative importance. These weighted criteria can be spatially integrated within a GIS-based multi-criteria evaluation framework to generate suitability maps for RHS deployment. In parallel, the FDEMATEL cause–effect structure can guide complementary policy and investment decisions by identifying leverage points—such as credit access, leadership support, or maintenance affordability—that require intervention before or alongside site selection. This combined approach enables planners to move from identifying important factors to making transparent, spatially explicit, and context-sensitive site selection decisions.

6. Conclusion

This study set out to address a key gap in RHS site selection research: the limited integration of livelihood dynamics into decision-making frameworks that are often dominated by technical and biophysical criteria. By embedding the SLF in a hybrid FDM–FAHP–FDEMATEL approach, the study systematically identified, prioritized, and mapped the causal interactions among determinants shaping RHS sustainability. The results demonstrate that while natural and physical factors such as rainfall remain indispensable enabling conditions, social and financial capitals function as the primary causal drivers governing whether technically suitable RHS sites translate into sustainable, long-term outcomes. The prioritization analysis showed that social, human, and financial capitals exert the greatest overall influence, while the cause–effect analysis revealed that social and financial capitals regulate the system by shaping access, coordination, affordability, and continuity. These findings refine existing RHS site selection models by explaining why technically viable locations may fail in practice when social organization or financial capacity is weak.

Rather than proposing a predictive or optimization tool, this study offers a conceptual decision-support framework that guides planners and policymakers in structuring site selection decisions. Practically, the framework helps decision-makers (i) distinguish between enabling environmental conditions and governing socio-economic drivers, (ii) identify leverage points—such as leadership support, access to credit, and maintenance affordability—that can be strengthened through complementary interventions, and (iii) design RHS projects that align technical feasibility with community readiness and financial sustainability. This moves site selection beyond ranking locations toward designing context-sensitive implementation strategies. The main contribution of this study lies in uncovering the specific causal pathways through which livelihood capitals interact to influence RHS success, thereby repositioning social cooperation and financial capacity as system-regulating forces rather than secondary considerations. Future applications of this framework can integrate the derived weights and causal structure into GIS-based suitability models or composite scoring systems, enabling spatially explicit and operational RHS site selection.

Despite its contributions, this study has several limitations. First, the analysis is grounded in the Somaliland context, and the expert judgments reflect the socio-economic, institutional, and environmental conditions specific to this setting. While this context provides valuable insight into water-stressed and resource-constrained environments, the relative importance and causal relationships among determinants may vary in other regions with different governance structures, climate regimes, or infrastructure capacities. Second, the study relies on expert-based evaluations, which may introduce subjective bias. Finally, the framework was applied analytically and has not yet been validated through field-based or spatial implementation. Future research should test and adapt the proposed framework across diverse geographical contexts using empirical case studies, GIS-based applications, and longitudinal performance assessments to enhance its generalizability.

CRediT authorship contribution statement

Abdiqani Muse Hassan: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdikarim Hassan Hussein:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Data curation, Conceptualization.

Declaration of competing interest

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

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