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Evaluating Nature-Based Solutions Implementation Factors in Urban Green Infrastructure Using SWARA in Fermatean Fuzzy Environment

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ABSTRACT

Nature-Based Solutions (NBSs) have emerged as effective approaches in urban planning by leveraging natural processes to address interconnected environmental, social, and economic challenges while enhancing the development of urban green infrastructure. However, despite increasing scholarly attention, their practical implementation remains constrained by the lack of systematic approaches for identifying and prioritizing key influencing factors. This study proposes a multi criteria decision making method in fuzzy environment, represented by Fermatean fuzzy Stepwise Weight Assessment Ratio Analysis (FF-SWARA) framework to evaluate the relative importance of factors affecting the successful implementation of NBSs in urban green infrastructure. Data were collected from four experts with relevant domain knowledge, who assessed six identified influential factors using linguistic evaluations. The results indicate that integrated governance strategies (C3) and financial resources and economic benefits (C4) are the most influential factors, highlighting their critical roles in facilitating effective NBS implementation.

1. Introduction

Urbanization and rapid land consumption have significantly changed urban landscapes, impeding the stability between constructed environments and natural ecosystems while enhancing the weakness of ecological and life-support systems [1]. These systems offer important ecosystem services that help urban sustainability and have therefore become a main center of planners and policymakers [2]. In response to the limitations of conventional infrastructure planning, researchers have promoted new frameworks that better address contemporary urban challenges [3]. Among these, Benedict and McMahon [4] Benedict and McMahon [4] introduced green infrastructure that emerged as a fundamental concept. Unlike gray infrastructure, green infrastructure consists of interconnected natural elements that provide indispensable ecosystem services and contribute to environmental sustainability [5, 6].

Despite continued investments in gray infrastructure, cities increasingly face environmental challenges [7]. These challenges highlight the need for integrated planning approaches that

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strengthen ecological resilience and improve resource efficiency [8]. Green infrastructure addresses these issues by connecting natural and built environments, delivering multiple ecosystem services while supporting sustainable urban development and climate resilience [9]. Nature-Based Solutions (NBSs) have emerged as an effective framework for planning and implementing urban green infrastructure. NBSs are nature-inspired interventions that address societal challenges while producing socio-economic and environmental advantages [10]. They contribute considerably to durable and resilient cities through the enhancement of biodiversity, improvement of ecosystem services, promotion of multifunctional landscapes, reduction of flood risks and urban heat, and strengthening of ecological connectivity [11, 12].

Although NBS research has significantly extended, various significant gaps remain. Existing studies show conceptual inconsistencies in defining and applying NBSs within urban green infrastructure [13, 14]. Moreover, research has predominantly emphasized governance and environmental aspects, while socio-economic and technical dimensions remain comparatively underexplored [15]. Although the environmental benefits and implementation barriers of NBSs are well recognized [16], quantitative assessments of their effectiveness are still limited. Furthermore, the heavy reliance on localized case studies [17, 18] has constrained theoretical development and reduced the generalizability of findings, highlighting the need for broader analytical frameworks and comparative research.

Zarei and Shahab [19] identified the key factors influencing the successful implementation of Nature-Based Solutions (NBSs) in urban green infrastructure across diverse urban contexts over the past decade. However, their study did not evaluate the relative importance of these factors from a managerial decision-making perspective. Multi-criteria decision-making (MCDM) approaches have been widely applied in various fields [20, 21] and have demonstrated their effectiveness in prioritizing complex factors. Therefore, this study develops a Fermatean fuzzy-based MCDM framework using a linguistically scaled Excel questionnaire to systematically assess and prioritize the influential factors affecting NBS implementation in urban green infrastructure. Data were collected from four experts, providing structured judgments for evaluating the significance of these factors.

The remaining of the study is as follows. Section 2 determines the literature review. In Section 3, the methodology is presented. Section 4 shows the application. Section 5 provides the conclusions and future recommendations.

2. Literature review

Various studies have been conducted related to nature-based solutions (NBSs) in urban green infrastructure. For instance, Previous studies have mainly explored Nature-Based Solutions (NBSs) through reviews, conceptual frameworks, assessment models, and case studies. Seddon *et al.,* [22] highlighted the potential of NBSs for addressing climate change while noting implementation limitations. Chausson *et al.,* [23] developed a global assessment framework and showed that NBS effectiveness varies across contexts. Albert *et al.,* [24] proposed planning principles emphasizing stakeholder participation and interdisciplinary approaches. Xing *et al.,* [25] classified NBS applications in the built environment and demonstrated their contribution to urban sustainability. Kooijman *et al.,* [26] and Randrup *et al.,* [27] emphasized innovation, entrepreneurship, and nature-based thinking as drivers for scaling NBSs. Calliari *et al.,* [28] developed an evaluation framework integrating climate adaptation and ecosystem services. Nesshöver *et al.,* [29] highlighted the importance of science–policy–practice integration, while Nelson *et al.,* [30] identified barriers including funding, governance, and knowledge gaps. Cohen-Shacham *et al.,* [31] proposed core principles for successful NBS implementation. Table 1 provides the studies related to NBS exploration

Table 1
Summary of previous studies on NBS implementation

Author	Method	Objective	Main findings
Seddon *et al.,* [22]	Literature review	Assess NBS potential and limitations	NBSs support climate action but require proper governance.
Chausson *et al.,* [23]	Systematic review and mapping	Evaluating NBS effectiveness	Effectiveness depends on ecosystem and context.
Albert *et al.,* [24]	Framework development	Guide NBS planning	Participation and interdisciplinary planning are essential.
Xing *et al.,* [25]	Classification analysis	Characterize NBS in built environments	NBSs improve urban sustainability and resilience
Kooijman *et al.,* [26]	Conceptual analysis	Explore NBS enterprises	Innovation and finance support scaling
Randrup *et al.,* [27]	Conceptual study	Develop nature-based thinking	Integrates ecological and social perspectives
Calliari *et al.,* [28]	Assessment framework	Evaluate climate-proof NBSs	Multi-dimensional indicators are needed
Nesshöver *et al.,* [29]	Interdisciplinary review	Link science, policy, and practice	Collaboration improves implementation
Nelson *et al.,* [30]	Critical review	Identify implementation challenges	Funding, governance, and knowledge gaps are key barriers
Cohen-Shacham *et al.,* [31]	Expert analysis and review	Define NBS principles	Stakeholder involvement and sustainability are critical

3. Methodology

Obtaining precise values in real-world decision-making is often difficult due to incomplete, vague, and non-numeric information provided by experts. Traditional deterministic methods are insufficient for handling such uncertainty. To address this limitation, Zadeh [32] introduced fuzzy sets (FSs) using linguistic variables to represent subjective judgments. However, FSs cannot fully capture hesitation and uncertainty. Atanassov [33] extended this concept by introducing intuitionistic fuzzy sets (IFSs) with membership and non-membership degrees, but their ability to represent complex ambiguity remains limited. Therefore, this study adopts the Fermatean fuzzy (FF) approach, which provides greater flexibility in modeling uncertainty and linguistic evaluations by allowing independent consideration of membership and non-membership information [34, 35]. The FF-SWARA method is subsequently employed to evaluate the factors influencing the successful implementation of nature-based solutions (NBSs) in urban green infrastructure.

Step 1. Experts have used the LVs from Table 2 to provide their opinions.

Step 2. These LVs are transformed to Fermatean fuzzy numbers (FFNs) and Fermatean fuzzy weighted geometric operator (FFWG) operator for aggregating the opinions of experts.

Step 3. There is a computation of scores valued related to aggregated experts' opinions.

Step 4. There is a criterion ranking from most important to less one according to their respective scores.

Step 5. There is a computation of associated significance $\left(c_j\right)$ of each criterion through the determination of differences between the scores of criteria (j) and the positive score of the criterion ranked just above it.

Table 2
Linguistic terms to evaluate the criteria

Linguistic Term	μ	v
Very High Importance-VHI	0.975	0.10
High Importance-HI	0.85	0.20
Medium High Importance-MHI	0.70	0.35
Fair Importance-FI	0.55	0.50
Medium Low Importance-MLI	0.35	0.70
Low Importance-LI	0.20	0.85
Very Low Importance-VLI	0.10	0.975

Step 6. Computation of comparative coefficient (p_j) of the criteria using Eq (1).

$$p_j = \begin{cases} 1, & j = 1 \\ c_j + 1, & j > 1 \end{cases} \tag{1}$$

Step 7. Determination of recomputed weights (q_j) through Eq (2).

$$q_j = \begin{cases} 1, & j = 1 \\ \frac{q_{(j-1)}}{p_j}, & j > 1 \end{cases} \tag{2}$$

Step 8. Obtention of final subjective weights of criteria using Eq (3).

$$w_j = \frac{q_j}{\sum_{j=1}^{n} q_j} \tag{3}$$

4. Application

The FF-SWARA method is applied to evaluate and rank the influential factors to successful implementation of NBS in urban infrastructure. To ensure a reliable assessment, we conducted interviews with four experts selected based on their background indicated in Table 3. Using Table 2, the experts provided their evaluations, which were subsequently used to assess the factors in Table 4.

Table 3
Participant's backgrounds

Experts	Gender	Profession	Sector/Role	Experience (Years)
E-1	Male	Urban planner and green infrastructure specialist	Government/urban planning authority	0-5 years
E-2	Male	Environment scientist and ecosystem management researcher	Academia/Research institution	5-10 years
E-3	Female	Environment policy and sustainability consultant	Consulting/policy advisor	0-5 years
E-4	Male	Landscape architect and NBS project coordinator	Private sector/ Urban design and development	5-10 years

Table 4
Factors to successful implementation of NBSs [19]

Factors	Description

Perspective of spatial justice in the implementation of NBS projects (C1)	Ensures fair access to green spaces and equitable distribution of NBS benefits.
Enhancing and ecosystem management (C2)	Improves ecosystem protection, restoration, and resilience.
Integrated governance strategies (C3)	Supports policy coordination and effective NBS decision-making.
Financial resources and economic benefits (C4)	Ensures funding availability and economic sustainability of NBS projects.
Technical knowledge and expertise (C5)	Provides skills and knowledge for NBS design and implementation.
Optimizing stakeholder engagement in NBS implementation (C6)	Promotes collaboration and participation among stakeholders.

4.1 Ranking of influential factors

Step 1. The factors are evaluated by the experts according to their knowledge and experience. Table 5 presented the compiled evaluations.

Table 5
Factors evaluations by each expert

Main Factors	E1	E2	E3	E4
C1	N	U	U	U
C2	M	S	S	N
C3	E	V	E	E
C4	V	V	I	I
C5	I	M	S	N
C6	I	V	M	M

Step 2. The FFNs are obtained through the conversion of LVs into numerical values. The assessment of the experts has been consolidated, as shown in Table 6. In our study, equal weight is provided for each expert assessment. The following example of step 2 computation for strategy S1 is shown:

= $(0.2)^{0.25}\times(0.1)^{0.25}\times(0.1)^{0.25}\times(0.1)^{0.25}$ =**0.272**

= $(1-(((1-(0.85^{3}))^{0.25})\times((1-(0.95^{0.3}))^{0.25})\times((1-(0.95^{0.3}))^{0.25})\times((1-(0.95^{0.3}))^{0.25})))^{1/3}$ = **0.935**

Table 6
Aggregated factors evaluations

Main criteria	μ	v
C1	**0.272**	**0.935**
C2	0.471	0.726
C3	0.936	0.140
C4	0.846	0.295
C5	0.545	0.685
C6	0.761	0.425

Steps 3-8. The determination of factor scores is made through the aggregation assessments offered in Table 6. These scores were then employed to rank the factors. The weights for each factor are employed and provided in Table 7, obtained from the next steps of our methodology.

The example of steps 3-8 calculation for factor C4 is as follows.

$=1+(0.846^{3})-(0.295^{3})$

=1.580

=1.818-1.580
=0.238
=0.238+1
=1.238
=1/1.238
=0.808
=0.808/ (1+0.808+0.664+0.436+0.390+0.257)
=0.227

Table 7
Results of the FF-SWARA application

Main criteria	Scores	c_j	k_j	q_j	Weights
C3	1.818		1	1	0.281
C4	**1.580**	**0.238**	**1.238**	**0.808**	**0.227**
C6	1.363	0.217	1.217	0.664	0.187
C5	0.841	0.523	1.523	0.436	0.123
C2	0.722	0.119	1.119	0.390	0.110
C1	0.203	0.519	1.519	0.257	0.072

In Table 8, it was revealed that the top two most influential factors for successful implementation of NBS are integrated governance strategies (C3) and financial resources and economic benefits (C4). Fig. 2 indicated the final weights of all the factors.

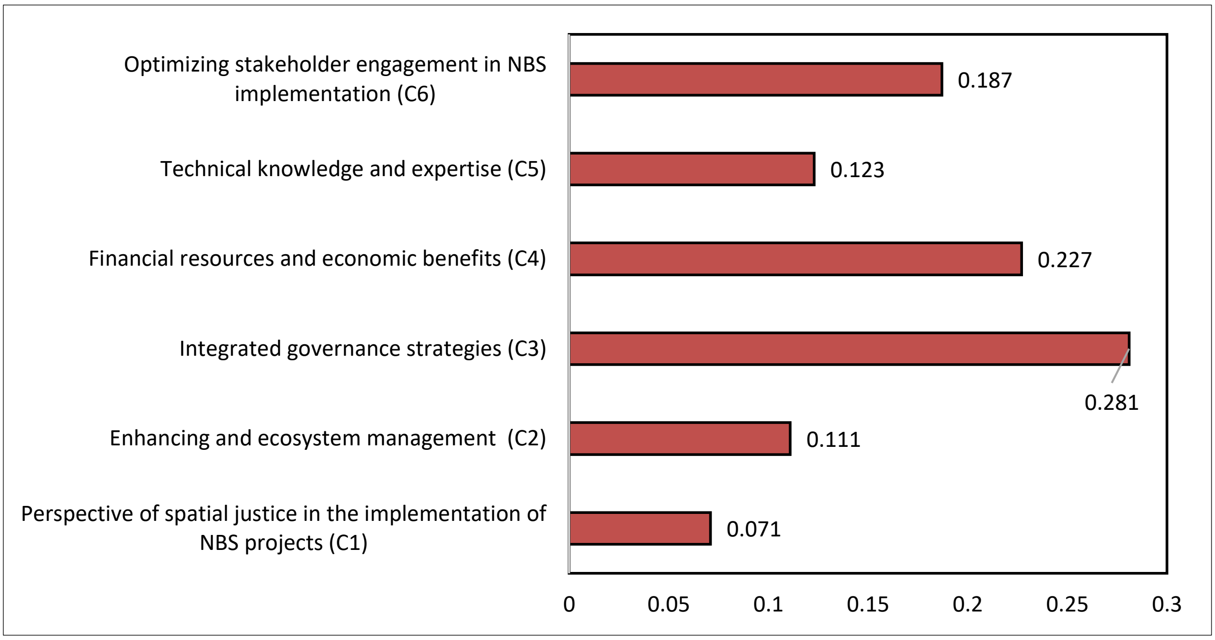

Fig. 1. Factors to successful implementation of nature-based solutions in green

5. Conclusions and future recommendations

This study applies a Fermatean fuzzy SWARA approach to assess the key factors influencing the successful implementation of nature-based solutions (NBSs) in urban infrastructure. Based on a comprehensive literature review, six evaluation factors were identified, and data were collected from four experts with relevant knowledge and experience. The findings reveal that integrated governance strategies (C3) and financial resources and economic benefits (C4) are the most critical factors for successful NBS implementation. Despite these contributions, the study has some limitations. The limited number of experts involved may affect the generalizability of the results; therefore, future research should include a larger group of experts and conduct assessments across broader regional or national contexts. Moreover, the proposed framework can be enhanced by integrating other uncertainty modeling approaches, such as Neutrosophic sets, Pythagorean fuzzy sets, and spherical fuzzy sets, to improve decision-making flexibility.

Author Contributions

The sole author did the Conceptualization of the study and adopted the methodology, analysis and wrote and edited the manuscript.

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Data Availability Statement

No data has been used for this study.

Conflicts of 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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