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Nature-based solutions for coastal protection based on intuitionistic fuzzy group decision making☆

Dong-Jiing Doong [a], Yu-Chen Lee [b,c,*], Peter Fröhle [d], Zoran Vojinovic [e], Cheng-Hui Liao [a]

[a] Department of Hydraulic and Ocean Engineering, National Cheng Kung University, University Rd. 1, Tainan, 70101, Taiwan
[b] Coastal Ocean Monitoring Center, National Cheng Kung University, University Rd. 1, Tainan, 70101, Taiwan
[c] Delft Center for Systems and Control, Mechanical Engineering, Delft University of Technology, Mekelweg 5, Delft, 2628 CD, South Holland, The Netherlands
[d] Institute of River and Coastal Engineering, Hamburg University of Technology, Denickestrasse 22, Hamburg, 21073, Germany
[e] IHE Delft Institute for Water Education, Westvest 7, Delft, 2611 AX, South Holland, The Netherlands

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ABSTRACT

Nature-based Solutions (NbS) use natural processes to address social, economic, and environmental challenges, including climate change, and this study explores their application for coastal protection. Before the actual implementation of NbS structures, co-creation with stakeholders to identify and assess potential NbS solutions for the selected local site is essential. However, existing frameworks for selecting NbS measures in coastal protection remain limited in handling the complex interactions among multiple indicators and the inherent uncertainty in expert evaluations. To address this gap, we develop an integrated assessment framework specifically for NbS in coastal protection. We first identified 18 distinct coastal protection measures through literature reviews. The proposed framework combines the Fuzzy Delphi Method (FDM) and entropy-based intuitionistic fuzzy TOPSIS (IF-TOPSIS) to facilitate expert-driven multi-criteria decision analysis (MCDA), both of which use fuzzy theory to address uncertainty and ambiguity in expert judgments. The 18 consensus indicators from an initial pool of 63 evaluation indicators are obtained in FDM analysis. Subsequently, IF-TOPSIS is applied to rank the 18 measures against these evaluation indicators based on membership, non-membership, and hesitancy degrees. The proposed framework is demonstrated through a case study at the Golden Coast, Tainan, Taiwan to illustrate its practical applicability.

1. Introduction

Nature-based Solutions (NbS) refer to strategic actions that address societal challenges arising from economic, social, and environmental factors through the sustainable use of natural systems (Cohen-Shacham et al., 2016; Santiago Fink, 2016; Dunlop et al., 2024). The concept of NbS was first introduced by the World Bank in a report submitted to the International Union for Conservation of Nature (IUCN) in 2008 (MacKinnon et al., 2008). It was defined as: "Actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits". Following the NbS concept, research has increasingly spanned multiple domains, including flood risk reduction (Vojinovic et al., 2021; Esraz-Ul-Zannat et al., 2024; Ruangpan et al., 2024), urban resilience (Bush and Doyon, 2019; Beceiro et al., 2022), drought and water management (Oral et al., 2020), air quality improvement (Marando et al., 2016), and climate change mitigation and adaptation (Johnson et al., 2022). This study focuses on coastal protection, where NbS show strong potential but also face challenges in selecting appropriate alternatives, which are addressed in this work.

Coastal hazards such as sea level rise, beach erosion, and storm surges are increasingly recognized as major global challenges, driven largely by climate change and the concentration of populations and infrastructure in coastal zones (Fröhle et al., 2011; Oumeraci et al., 2015; Dreier et al., 2021). Coastal hazards can lead to significant economic losses, particularly in densely populated coastal cities and residential areas across Asia (Neumann et al., 2015). During extreme storms, wave overtopping intensifies coastal flooding and infrastructure damage, creating severe risks for urban areas at low elevations (Peng and Zou, 2011). In Taiwan, typhoons are the primary natural drivers of coastal disasters, occurring on average 3 to 5 times per year and generating extreme wave loading and storm surges that cause significant structural damage and flood risk (Doong et al., 2016). There

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* Corresponding author at: Coastal Ocean Monitoring Center, National Cheng Kung University, University Rd. 1, Tainan, 70101, Taiwan.
E-mail address: 10808066@gs.ncku.edu.tw (Y.-C. Lee).

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is an urgent need to advance disaster risk reduction and adaptation strategies such as coastal protection structures to effectively reduce the actual impacts on coastal regions (Busayo and Kalumba, 2020). Coastal protection structures serve two primary functions in hazard mitigation: storm protection, such as wave attenuation, and erosion control, such as sediment accretion and stabilization (Jordan and Fröhle, 2022). Numerous research studies have experimentally and theoretically investigated wave attenuation by vegetation in both laboratory and field settings (Anderson and Smith, 2014; Rupprecht et al., 2017; Li et al., 2024). Different nature-based solutions (NbS) exhibit varying effectiveness in hazard mitigation. For instance, coral reefs can reduce incoming wave heights by up to 70%, salt marshes by 72%, mangroves by 31%, and seagrass or kelp beds by 36% (Narayan et al., 2016). However, some NbS measures are highly site specific making their implementation and assessment difficult in other locations (Narayan et al., 2016; Chausson et al., 2020; Alves et al., 2024).

Selecting appropriate NbS involves multiple challenges that highlight the need for systematic and practical frameworks (Sowińska-Świerkosz and García, 2021; Wickenberg et al., 2021; Gonzalez-Ollauri et al., 2023). Recent research shows that NbS frameworks are often designed to address specific problems by adapting interventions to local needs and priorities (Raymond et al., 2017; de Lima et al., 2022; Wójcik-Madej et al., 2025). To select the most appropriate NbS measures, decision support tools such as multi-criteria decision analysis (MCDA) have been widely adopted in the assessment of NbS options. MCDA enables the systematic evaluation of environmental interventions by balancing ecological, social, and economic priorities through a set of decision-making methods such as the Analytical Hierarchy Process (AHP) (Saaty, 1980; Karleuša et al., 2020), the preference ranking organization method for enrichment evaluation (PROMETHEE) (Gravas et al., 2022; Sauvé et al., 2022), the analytical network process (ANP) (Handayani et al., 2021), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang et al., 1981; Madanchian and Taherdoost, 2023). It can deal with conflicting criteria simultaneously such as cost-effectiveness, stakeholder acceptability, and ecosystem service provision based on decision maker and stakeholder considerations (Ferretti and Montibeller, 2016; Marttunen et al., 2017). A key component of MCDA is the weighting mechanism, which serves as a formalized approach to prioritizing criteria and reflects their relative importance in alignment with the decision-maker's value system (Ayan et al., 2023; Vagiona, 2025). As a result, MCDA enables the integration and comparison of both qualitative and quantitative outcomes (Drake et al., 2017). Several successful studies have already applied MCDA methods to address coastal challenges, including coastal protection (Chang et al., 2012; Kaya et al., 2024), coastal wetlands ecotourism (Lin and Chuang, 2012) and coastal flood hazard management (Nguyen et al., 2020; Sun et al., 2024).

While MCDA such as TOPSIS are effective in ranking alternatives based on established evaluation indicators, the identification and validation of these indicators often depend on expert judgment and this may not adequately address the inherent uncertainty and subjectivity in expert opinions (Pham et al., 2017; Nguyen, 2022). The traditional Delphi method is a process used to gather expert opinions and reach consensus on complex issues (Dalkey and Helmer, 1963). Since the traditional Delphi Method cannot adequately represent results in quantitative terms, researchers developed the Fuzzy Delphi Method (FDM) by considering fuzzy set theory concepts (Murray et al., 1985). Fuzzy set theory allows experts to express their judgments through linguistic variables, resembling human reasoning by using approximate information and handling uncertainty (Zadeh, 1965; Bellman and Zadeh, 1970). Fuzzy Delphi Method yields objective and reliable results even when based on a small number of expert participants (Ma et al., 2011). It not only minimizes the time and cost involved in gathering expert opinions but also ensures that these judgments are accurately and faithfully represented (Ishikawa et al., 1993; Kuo and Chen, 2008). On the basis of these attributes, the main aim of this study is to develop an expert-informed decision-making framework for selecting suitable NbS measures for coastal protection, which can provide practical guidance for subsequent engineering planning by engineers or governments.

In this study, 18 coastal protection measures were initially collected through a literature review, all of which are existing coastal engineering structures based on NbS. We then develop a decision-making framework that integrates the Fuzzy Delphi Method (FDM) with the entropy-weighted TOPSIS approach to support the selection of NbS coastal protection measures. The proposed method begins with FDM to engage expert judgment in identifying and refining relevant evaluation indicators. Subsequently, the entropy method is applied to assign objective weights based on the variability of performance data, followed by the use of IF-TOPSIS to rank alternative NbS measures. A distinctive feature of this study is the integration of expert insights from individuals with deep knowledge of NbS and substantial field experience. The use of expert judgment enhances the efficiency and suitability of NbS selection by ensuring that the solutions adapted to specific local conditions. Meanwhile, to demonstrate the applicability of the framework, a case study is conducted in the Golden Coast area of Tainan, Taiwan. This framework enables coastal engineers to quantify trade-offs between coastal structural performance and ecosystem co-benefits in decision-making that moves beyond traditional gray infrastructure design.

This paper is structured as follows. Section 1 introduces the concept of NbS and provides the background and objectives related to coastal protection. Section 2 outlines the selected 18 NbS measures for coastal protection and proposed NbS assessment framework developed in this study. Section 3 demonstrates the application of the framework through a case study analysis. Finally, Section 4 summarizes the key findings and offers concluding remarks. We also include Appendix A providing a review of the 18 NbS measures for coastal protection and Appendix B presenting the questionnaires used in this study.

2. Proposed NBS assessment framework for coastal protection

2.1. Identification of nature-based solutions for coastal protection

Through an extensive literature review, we identified a total of 18 representative NbS measures relevant to coastal protection. The scenarios showing how the 18 NbS coastal protection measures are deployed at the coast are presented in Fig. 1. Our review indicates that most structures have already been constructed in coastal field sites worldwide for coastal protection and have demonstrated their effectiveness to governments, scientists, and engineers. A detailed review of each measure is provided in Appendix A.

Meanwhile, we show how different measures function for coastal protection (including wave control and erosion control) and ecological system services, as shown in Table 1. It can be observed that different NbS measures have distinct characteristics in terms of coastal protection and the provision of various ecological system services (Jordan and Fröhle, 2022). For example, mangroves play an important role in wave attenuation, reducing current velocity and wind speed, which contributes to effective wave control (Bao, 2011; Beck and Lange, 2016). They also support sediment accumulation, stabilize the ground soil, and reduce shear stress, all of which help control coastal erosion (Barbier et al., 2011; Gedan et al., 2011; Narayan et al., 2016). Meanwhile, mangroves also provide strong provisioning and regulating services (Barbier et al., 2011; Gedan et al., 2011). This summarized table will assist experts in considering different factors such as functions related to coastal protection and ecological ecosystem services for developing the subsequent assessment framework.

2.2. Proposed a NbS assessment framework for coastal protection

Building on existing NbS frameworks, this study integrates them and proposes a comprehensive NbS assessment framework for coastal

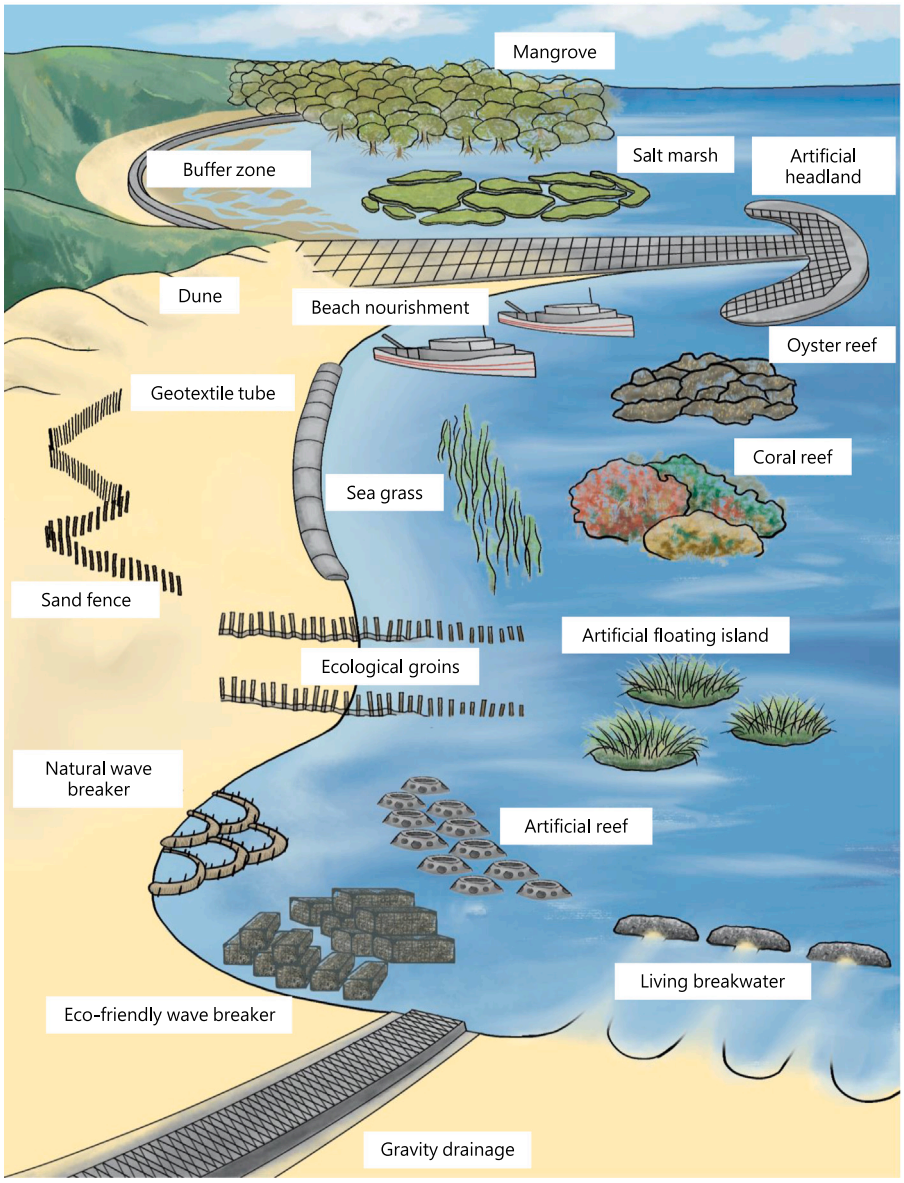


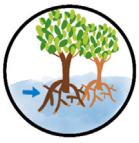
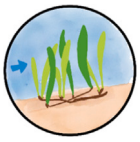
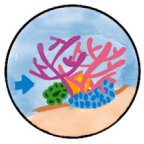
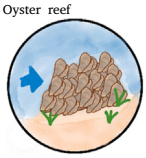
Fig. 1. 18 coastal protection measures.

protection. The proposed framework consists of sequential steps including identifying challenges, assessing, project planning, implementing, monitoring and evaluating, and governance, as illustrated in Fig. 2. The development process and detailed description of the framework are provided in the supplemental material titled 'Proposed NbS Assessment Framework for Coastal Protection'. Following the NbS project cycle, our study specifically focuses on "Step 2: Assessing" by developing a robust decision support approach that systematically evaluates potential NbS for coastal protection. The assessment proposed here is demonstrated in Fig. 3. Our approach integrates two methodologies: the Fuzzy Delphi Method (FDM) for consensus-driven criteria selection and the intuitionistic fuzzy Technique for Order of Preference by Similarity to Ideal Solution (IF-TOPSIS) for systematic alternative ranking.

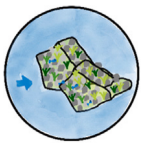
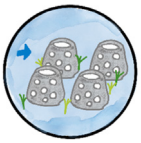
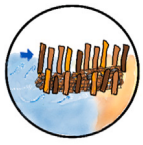
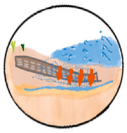
The first part uses FDM to identify evaluation indicators for the assessment of NbS measures. This process begins with stakeholder engagement, where expert questionnaires are designed and distributed to diverse participants such as coastal engineers, ecologists, community representatives, and policy makers. The FDM approach captures the inherent uncertainty and subjectivity in expert opinions by converting linguistic assessments into triangular fuzzy numbers, enabling more accurate representation of expert knowledge. Through iterative rounds of consultation, we collect expert opinions on indicator importance across multiple dimensions including environmental effectiveness (e.g., wave attenuation capacity, biodiversity enhancement), economic efficiency (e.g., cost–benefit ratios, maintenance requirements), and social acceptability (e.g., community support, recreational co-benefits). The consensus degree is systematically analyzed using the gray zone method, ensuring that only indicators achieving sufficient expert agreement are retained for final evaluation (Sowińska-Świerkosz and García, 2021).

The second part applies the IF-TOPSIS to rank alternative NbS measures based on the evaluation indicators established through FDM. This multi-criteria decision analysis technique provides a systematic approach to evaluate complex trade-offs inherent in coastal NbS selection, addressing the challenge of comparing 18 NbS interventions selected in this study. The IF-TOPSIS process begins with questionnaire design that captures stakeholder preferences for different NbS alternatives across the established evaluation indicators. Decision matrices are normalized to ensure comparability across different measurement

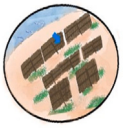
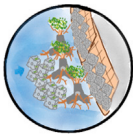
Table 1
Coastal protection structures characteristics.

No.	1	2	3	4	5	6
Structures	Mangrove	Salt marsh	Seagrass	Dune	Coral reef	Oyster reef
						
Wave Control						
Wave attenuation	✓	✓	✓	✓	✓	✓
Wave breaking				✓	✓	
Reduction of current velocities	✓	✓	✓	✓		
Water retaining capacity		✓				
Wind speed reduction	✓					
Erosion Control						
Sediment accretion	✓	✓	✓	✓	✓	✓
Ground soil stabilization	✓	✓	✓			✓
Reduction of shear stresses	✓	✓			✓	✓
Sediment exchange and storage				✓		
Ecological System Services						
Supporting Services	⊙	◉	◉	◉	⊙	◉
Provisioning Services	◉	⊙	⊙	◉	◉	◉
Regulating Services	⊙	⊙	◉	⊙	○	◉
Cultural Services	◉	⊙	⊙	◉	◉	○

Service Capacity: Low: ○ Medium: ⊙ High: ◉

No.	7	8	9	10	11	12
Structures	Beach nourishment	Buffer zone	Living breakwater	Artificial reef	Permeable pile groins	Gravity drainage
						
Wave Control						
Wave attenuation	✓	✓	✓	✓	✓	✓
Wave breaking	✓	✓	✓	✓	✓	
Reduction of current velocities		✓	✓	✓	✓	✓
Water retaining capacity		✓				✓
Wind speed reduction						
Erosion Control						
Sediment accretion	✓	✓		✓	✓	✓
Ground soil stabilization	✓	✓	✓	✓	✓	✓
Reduction of shear stresses	✓	✓	✓	✓	✓	✓
Sediment exchange and storage	✓	✓			✓	
Ecological System Services						
Supporting Services	⊙	◉	◉	◉	○	○
Provisioning Services	⊙	⊙	◉	⊙	⊙	○
Regulating Services	◉	⊙	⊙	⊙	⊙	⊙
Cultural Services	◉	◉	⊙	⊙	⊙	⊙

Service Capacity: Low: ○ Medium: ⊙ High: ◉

No.	13	14	15	16	17	18
Structures	Geotextile tube	Artificial headland	Sand fence	Artificial floating island	Natural wave breaker	Eco-friendly wave breaker
						
Wave Control						
Wave attenuation	✓	✓			✓	✓
Wave breaking	✓			✓	✓	✓
Reduction of current velocities	✓	✓		✓	✓	✓
Water retaining capacity		✓			✓	
Wind speed reduction			✓			
Erosion Control						
Sediment accretion	✓	✓	✓	✓	✓	
Ground soil stabilization	✓	✓	✓		✓	✓
Reduction of shear stresses	✓	✓		✓	✓	✓
Sediment exchange and storage		✓	✓		✓	✓
Ecological System Services						
Supporting Services	○	⊙	○	◉	◉	◉
Provisioning Services	○	○	○	◉	⊙	⊙
Regulating Services	○	⊙	⊙	⊙	◉	⊙
Cultural Services	⊙	⊙	⊙	⊙	⊙	⊙

Service Capacity: Low: ○ Medium: ⊙ High: ◉

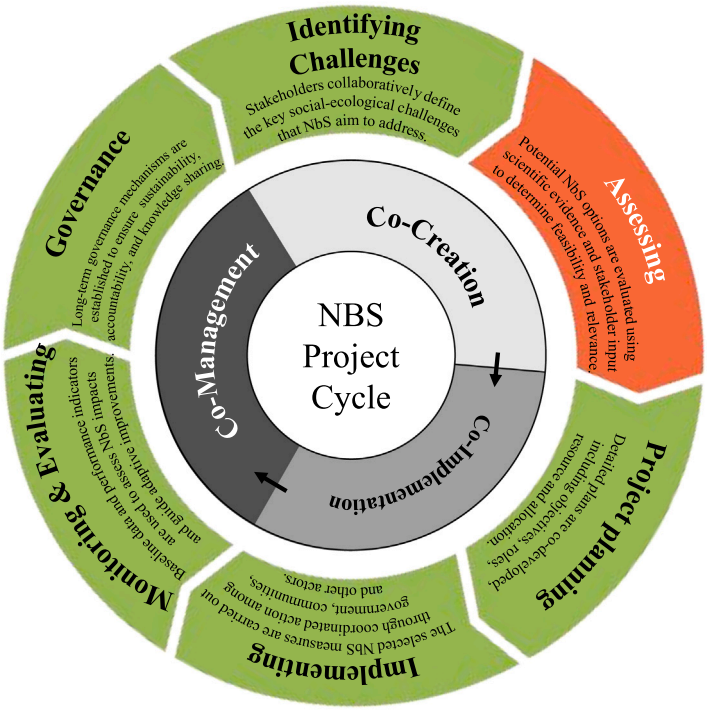


Fig. 2. Framework for the NbS Project Cycle: Integrating Co-Creation, Co-Implementation and Co-Management. *Source:* Modified from Dumitru and Wendling (2021).

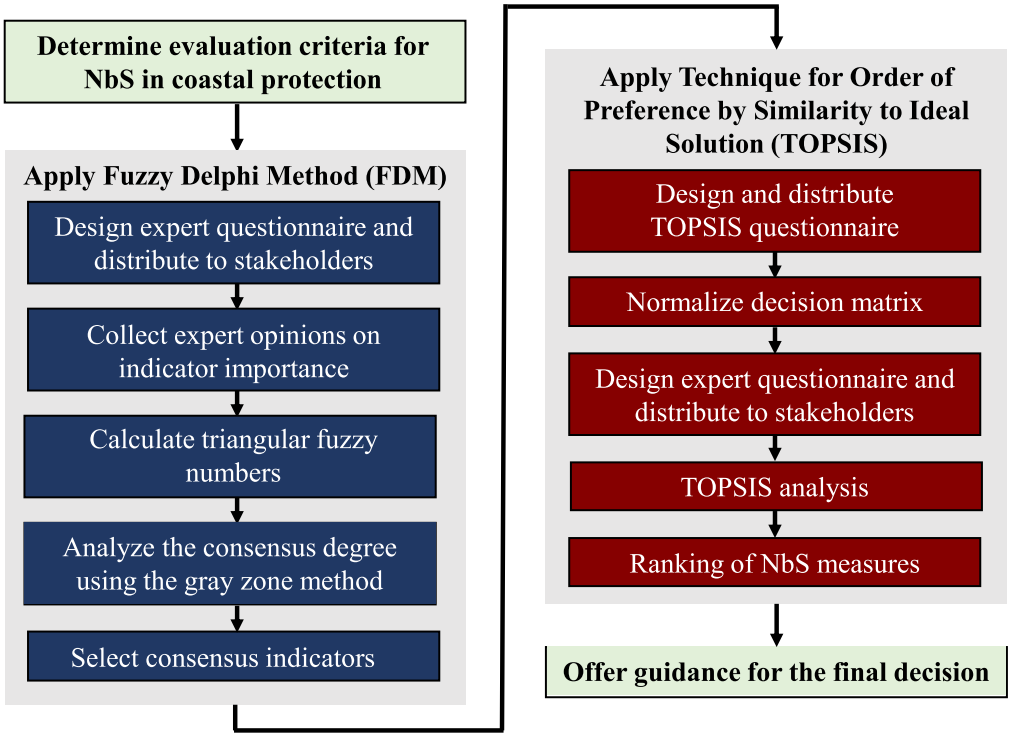


Fig. 3. Proposed assessment framework for evaluating NbS in coastal protection. The process begins with defining evaluation indicators and applying the Fuzzy Delphi Method (FDM) to identify consensus indicators based on expert input. These indicators are then ranked using the intuitionistic fuzzy Technique for Order of Preference by Similarity to Ideal Solution (IF-TOPSIS) to guide final decision-making.

scales and units, while expert questionnaires are distributed to gather performance assessments for each NbS option. The IF-TOPSIS systematically calculates the relative closeness of each alternative to the ideal solution, generating rankings of NbS measures. This dual approach not only addresses uncertainty and subjectivity in expert assessments but also enables the comparison of complex alternatives in a consistent manner. The theoretical background and procedural steps for FDM and IF-TOPSIS are introduced below.

2.3. Research methods employed in this framework

2.3.1. Fuzzy Delphi Method

The Fuzzy Delphi Method (FDM) was used to establish a consensus-based evaluation framework by systematically integrating expert judgments while addressing linguistic ambiguity and uncertainty (Murray et al., 1985; Roostaee et al., 2013; Bui et al., 2020). This method integrates the traditional Delphi Method (Dalkey and Helmer, 1963; Mayne, 1990) with fuzzy theory to address the shortcomings of the traditional approach (Huang and Peng, 2023). To enhance the robustness of expert-based evaluations under uncertainty, intuitionistic fuzzy sets (IFS), introduced by Atanassov in the 1980s (Atanassov, 1988; Atanassov and Atanassov, 1999), extend classical fuzzy set theory. Unlike conventional fuzzy sets, IFS assigns to each element three independent parameters: a membership degree, a non-membership degree and a hesitation degree. This explicit representation of indeterminacy enables more realistic modeling of vague, incomplete, or conflicting expert judgments, making IFS particularly effective for decision-making, risk assessment, and multi-criteria expert evaluation. Building upon the traditional Delphi Method, the Fuzzy Delphi Method reduces the number of survey rounds, allows expert opinions to be expressed more comprehensively, enhances the rationality of expert knowledge, and is more economical in terms of time and cost (Yao et al., 2022). Within the FDM, double triangle fuzzy numbers were used to establish expert consensus, and the gray zone test method was employed to verify whether expert opinions consistently converged (Yao et al., 2022, 2024). We summarize the steps to apply the FDM based on the literature (Chang et al., 2013; Tseng et al., 2022; Yao et al., 2022, 2024), which will be used in this study and are described as follows:

Step 1: Questionnaire design and survey

A questionnaire was developed based on the structure of the NbS evaluation indicators, as shown in Table B.11 in Appendix B. Details regarding the experts and stakeholders in our case study can be found in the next section. Each stakeholder was asked to rate the importance of each indicator on a scale from 0 to 10. The lowest score provided by each stakeholder represents their most pessimistic cognitive value (i.e., the minimum acceptable importance), while the highest score represents their most optimistic cognitive value (i.e., the maximum acceptable importance). Additionally, each expert was required to indicate their personal perceived value for each indicator.

Step 2: Calculating minimum and maximum cognitive values

The collected pessimistic and optimistic scores were subjected to statistical analysis to ensure the reliability of the data. Outliers exceeding two standard deviations from the mean were excluded. For each indicator i, the remaining values were then used to calculate the following parameters: the minimum value C_L^i, geometric mean C_M^i, and maximum value C_U^i for the pessimistic evaluations and the minimum value O_L^i, geometric mean O_M^i, and maximum value O_U^i for the optimistic evaluations. These statistical measures serve as the basis for constructing the triangular fuzzy numbers in the subsequent step of the Fuzzy Delphi Method.

Step 3: Constructing triangular fuzzy numbers

Triangular fuzzy numbers were then constructed for each indicator based on the previously calculated statistical values. For the pessimistic evaluations, the fuzzy number was defined as $C^i = (C_L^i, C_M^i, C_U^i)$. Similarly, for the optimistic evaluations, the fuzzy number was defined as $O^i = (O_L^i, O_M^i, O_U^i)$. These triangular fuzzy numbers serve as the foundational representations of expert opinions in the fuzzy environment.

Step 4: Calculating consensus values using gray area analysis

Consensus among experts was assessed using a gray area test, based on the overlap between the pessimistic and optimistic fuzzy numbers. Three scenarios were evaluated, as shown in Fig. 4 from (a) to (c):

- Case 1: No overlap
  If $C_U^i \le O_L^i$, there is no overlap between fuzzy numbers, indicating strong expert consensus. The consensus value G^i is calculated as the arithmetic mean of the two geometric means:
  $$G^i = \frac{C_M^i + O_M^i}{2} \tag{1}$$
- Case 2: Partial overlap
  If $C_U^i > O_L^i$ and the gray area Z^i is less than the difference between the geometric means ($Z^i < M^i$), this reflects moderate divergence with minor disagreement. The gray area is defined as $Z^i = C_U^i - O_L^i$, and the geometric mean difference is defined as $M^i = O_M^i - C_M^i$. Under these conditions, the consensus value G^i is calculated as:
  $$G^i = \frac{(C_U^i \cdot O_M^i) - (O_L^i \cdot C_M^i)}{(O_M^i - O_L^i) + (C_U^i - C_M^i)} \tag{2}$$
- Case 3: Significant overlap
  If $Z^i > M^i$, expert opinions are highly divergent, and the indicator is excluded from further analysis due to insufficient consensus. Such a scenario suggests that experts providing extremely conservative maximum values (C_U^i) and optimistic minimum values (O_L^i) differ significantly from those of other experts. In this case, a further round of questionnaires is required to address the divergence.

Step 5: Threshold-based selection

Finally, an indicator is retained if its consensus value G^i exceeds a predetermined threshold, typically between 6.0 and 8.0 (Tseng et al., 2022; Shao et al., 2023). This threshold ensures that only indicators with adequate expert agreement are considered important and included in the final set. The selection condition can be expressed as:

$$G^i = \left\{ x_j \middle| \max U_{F^i}(x_j) \right\} \tag{3}$$

where $U_{F^i}(x_j)$ represents the membership function of the fuzzy consensus value for indicator i, and x_j is the score at which the membership degree reaches its maximum.

2.3.2. Intuitionistic fuzzy TOPSIS method

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), originally proposed by Hwang and Yoon, is a widely used MCDA method. It evaluates alternatives based on their geometric distance from the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS), selecting the option closest to the PIS and farthest from the NIS to determine the optimal choice (Hwang et al., 1981). Building on this foundation, Roszkowska and Filipowicz-Chomko (2021) extended the TOPSIS procedure by constructing both PIS and NIS to specific decision targets, thereby enhancing the method's flexibility and adaptability to complex decision environments (Roszkowska et al., 2021). More details on the TOPSIS method can be found in several review papers (Behzadian et al., 2012; Emrouznejad and Marra, 2017; Çelikbilek and Tüysüz, 2020; Pandey et al., 2023).

To address the inherent uncertainty, vagueness and imprecision in human judgments, the intuitionistic fuzzy TOPSIS (IF-TOPSIS) has been developed as an extension of the classical TOPSIS approach (Chen, 2000; Memari et al., 2019; Roszkowska et al., 2021). The IF-TOPSIS enhances decision-making under uncertainty by considering membership, non-membership, and hesitancy degrees, thus offering a clearer representation of expert opinions (Roszkowska et al., 2021). The standard procedure of IF-TOPSIS involves several key steps: collecting intuitionistic fuzzy performance ratings, constructing decision matrices,

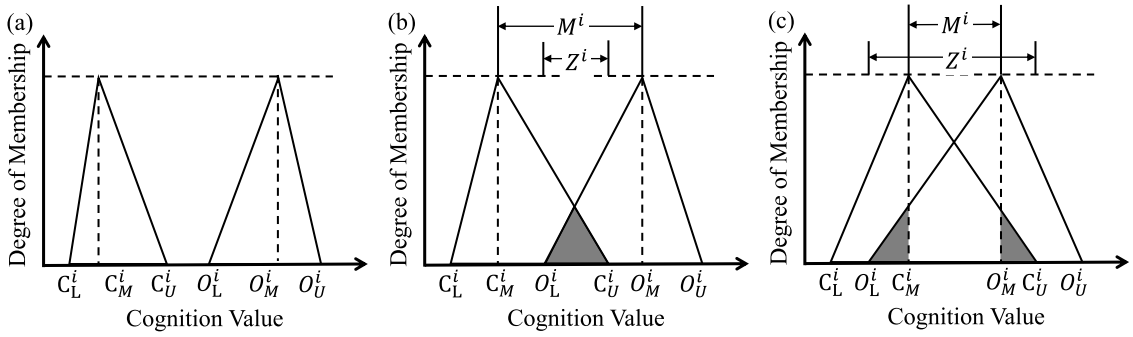


Fig. 4. Double triangular fuzzy numbers. (a) Case 1 (b) Case 2 (c) Case 3.

determining ideal solutions, computing distances using appropriate metrics, calculating relative closeness coefficients, and ranking the alternatives accordingly (Yang et al., 2017; Daneshvar Rouyendegh et al., 2018; Roszkowska et al., 2021). However, in the TOPSIS method, subjectivity in determining criteria weights can influence the final result and reliability of the decision made (Sulistiani et al., 2024). The selection of experts to assign the weights is consequently important.

In this study, we integrate the entropy weight method with TOPSIS, which enhances decision objectivity by quantifying criteria importance through data dispersion analysis. The entropy weight method assigns weights to indicators based on their ability to discriminate among alternatives (Yang et al., 2017). Indicators with greater variability in performance values across alternatives are assigned higher weights, as they provide more information for distinguishing between options. In contrast, indicators with uniformly distributed performance values receive lower weights due to their limited contribution to the differentiation process. Expert responses gathered through a questionnaire were used as input for the IF-TOPSIS method to assess the importance of indicators. The questionnaire used for the IF-TOPSIS analysis is shown in Table B.12 in Appendix B. Details regarding the experts and stakeholders in our case study can be found in the next section.

The detailed steps of the IF-TOPSIS method combined with the entropy weight approach are as follows:

Step 1. Construct the Decision Matrix

After finalizing the evaluation indicators and alternatives through the intuitionistic fuzzy Delphi method, experts provide linguistic evaluations that are converted into intuitionistic fuzzy numbers (IFNs), resulting in a decision matrix $D^{(k)}$ of size $m \times n$, where m is the number of alternatives and n is the number of indicators. Each expert k provides a decision matrix $D^{(k)}$ defined as:

$$D^{(k)} = \left(\alpha_{ij}^{(k)}\right)_{m\times n} = \begin{pmatrix} \alpha_{11}^{(k)} & \alpha_{12}^{(k)} & \cdots & \alpha_{1n}^{(k)} \\ \alpha_{21}^{(k)} & \alpha_{22}^{(k)} & \cdots & \alpha_{2n}^{(k)} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{m1}^{(k)} & \alpha_{m2}^{(k)} & \cdots & \alpha_{mn}^{(k)} \end{pmatrix} \tag{4}$$

Each element $\alpha_{ij}^{(k)} = \left(\mu_{ij}^{(k)}, \nu_{ij}^{(k)}, \pi_{ij}^{(k)}\right)$ denotes the intuitionistic fuzzy number provided by expert k for evaluating the ith alternative under the jth indicator. $\mu_{ij}^{(k)} \in [0,1]$ is the membership degree indicating the degree of support. $\nu_{ij}^{(k)} \in [0,1]$ is the non-membership degree indicating the degree of opposition. $\pi_{ij}^{(k)} = 1 - \mu_{ij}^{(k)} - \nu_{ij}^{(k)}$ is the hesitancy degree representing the uncertainty in the evaluation.

Step 2. Calculate Expert Weights Using Entropy Method

To objectively measure the reliability and informativeness of each expert's intuitionistic fuzzy evaluation, an entropy-based weighting approach is adopted. First, define two crisp reference intuitionistic fuzzy numbers: $\bar{F} = (1, 0, 0)$ representing full membership and maximal support, and $\underline{F} = (0, 1, 0)$ representing full non-membership and maximal opposition. The normalized Hamming distance between two intuitionistic fuzzy numbers $a = (\mu_a, \nu_a, \pi_a)$ and $b = (\mu_b, \nu_b, \pi_b)$ is given by:

$$d_H(a,b) = \frac{1}{2}\left(|\mu_a - \mu_b| + |\nu_a - \nu_b| + |\pi_a - \pi_b|\right) \tag{5}$$

The entropy value for each expert's evaluation is then calculated as:

$$e_{ij}^{(k)} = \frac{\min\left\{d_H\left(\alpha_{ij}^{(k)}, \bar{F}\right),\ d_H\left(\alpha_{ij}^{(k)}, \underline{F}\right)\right\}}{\max\left\{d_H\left(\alpha_{ij}^{(k)}, \bar{F}\right),\ d_H\left(\alpha_{ij}^{(k)}, \underline{F}\right)\right\}} \tag{6}$$

This normalized ratio guarantees that the entropy value always lies in $[0,1]$, with lower values corresponding to more informative expert judgments.

The normalized entropy-based weight assigned to each expert for every alternative indicator pair is:

$$w_{ij}^{(k)} = \frac{1 - e_{ij}^{(k)}}{\sum_{k=1}^{l}(1 - e_{ij}^{(k)})} \tag{7}$$

where l is the total number of experts. In this way, experts providing more decisive evaluations receive greater weight in the IFWA aggregation. This approach ensures that the consensus decision matrix reflects both the content and certainty of each expert's intuitionistic fuzzy judgment.

Step 3. Integrate Expert Weights

Using the intuitionistic fuzzy Weighted Averaging (IFWA) operator (Xu, 2007), the aggregated evaluation α_{ij} for alternative A_i under indicator C_j is:

$$\alpha_{ij} = IFWA_{w_{ij}^{(k)}}(\alpha_{ij}^{(1)}, \alpha_{ij}^{(2)}, \ldots, \alpha_{ij}^{(l)}) \tag{8}$$

with membership and non-membership degrees computed as:

$$\mu_{ij} = 1 - \prod_{k=1}^{l}(1 - \mu_{ij}^{(k)})^{w_{ij}^{(k)}} \tag{9}$$

$$\nu_{ij} = \prod_{k=1}^{l}(\nu_{ij}^{(k)})^{w_{ij}^{(k)}} \tag{10}$$

$$\pi_{ij} = 1 - \mu_{ij} - \nu_{ij} \tag{11}$$

Once all aggregated evaluations are computed, the integrated decision matrix D' is then constructed as:

$$D' = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{m1} & \alpha_{m2} & \cdots & \alpha_{mn} \end{pmatrix} \tag{12}$$

Each element α_{ij} represents the group-based intuitionistic fuzzy evaluation of alternative with respect to indicator, considering all expert inputs and their corresponding weights.

Step 4. Calculate Attribute Weights Using Entropy in an intuitionistic fuzzy Environment

To determine the importance of each indicator, the entropy method for intuitionistic fuzzy sets originally proposed by Szmidt and Kacprzyk (2001, 2005) is applied. Given the aggregated intuitionistic fuzzy decision matrix $\alpha_{ij} = (\mu_{ij}, \nu_{ij}, \pi_{ij})$, entropy is calculated as:

$$e_{ij} = \frac{\pi_{ij}}{1 - \min(\mu_{ij}, \nu_{ij})} \tag{13}$$

This ratio measures the uncertainty in the assessment, accounting for both positive and negative evidence. We then compute the average entropy for each indicator j over all alternatives:

$$\bar{e}_j = \frac{1}{m} \sum_{i=1}^{m} e_{ij}, \tag{14}$$

where m is the number of alternatives. The attribute weight W_j is derived by normalizing the complement of the entropy:

$$W_j = \frac{1 - \bar{e}_j}{\sum_{j=1}^{n} (1 - \bar{e}_j)}, \tag{15}$$

where n is the total number of indicator and the weights satisfy $\sum_{j=1}^{n} W_j = 1$. A lower entropy leads to a higher weight, reflecting greater decisiveness of that indicator.

Step 5. Construct the Weighted intuitionistic fuzzy Decision Matrix

Using the computed weights W_j for each indicator, the weighted decision matrix $V = (v_{ij})$ is formed by multiplying each intuitionistic fuzzy value α_{ij} by its corresponding weight W_j:

$$v_{ij} = W_j \otimes \alpha_{ij} = \left(\mu^*_{ij}, \nu^*_{ij}, \pi^*_{ij}\right), \tag{16}$$

where

$$\mu^*_{ij} = W_j \cdot \mu_{ij},$$
$$\nu^*_{ij} = W_j \cdot \nu_{ij},$$
$$\pi^*_{ij} = W_j \cdot \pi_{ij}.$$

The resulting matrix V thus captures both the performance of each alternative and the relative importance of each indicator. It will be used in the subsequent steps to identify the positive and negative ideal solutions and to compute the closeness coefficients for ranking the alternatives.

Step 6. Determine Positive and Negative Ideal Solutions

The next step is to identify the Positive Ideal Solution (PIS) A^* and Negative Ideal Solution (NIS) A^- for each indicator

$$A^* = v^*_j = \left(\mu^*_j, \nu^*_j, \pi^*_j\right) = \left(\max_i \mu_{ij},\ \min_i \nu_{ij},\ \min_i \pi_{ij}\right) \tag{17}$$

$$A^- = v^-_j = \left(\mu^-_j, \nu^-_j, \pi^-_j\right) = \left(\min_i \mu_{ij},\ \max_i \nu_{ij},\ \max_i \pi_{ij}\right) \tag{18}$$

The positive ideal solution A^* serves as the best performing alternative, while the negative ideal solution A^- represents the worst.

Step 7. Calculate Distances to Ideal Solutions

In this step, the proximity of each alternative to the ideal solutions is quantified using a normalized Euclidean distance metric specifically adapted for intuitionistic fuzzy numbers. The distance to the positive ideal solution S^*_i, and the distance to the negative ideal solution S^-_i are computed as:

$$S^*_i = d_E(v_i, v^*) = \sqrt{\frac{1}{2n} \sum_{j=1}^{n} \left[(\mu_{v_{ij}} - \mu_{v^*_j})^2 + (v_{v_{ij}} - v_{v^*_j})^2 + (\pi_{v_{ij}} - \pi_{v^*_j})^2\right]} \tag{19}$$

$$S^-_i = d_E(v_i, v^-) = \sqrt{\frac{1}{2n} \sum_{j=1}^{n} \left[(\mu_{v_{ij}} - \mu_{v^-_j})^2 + (v_{v_{ij}} - v_{v^-_j})^2 + (\pi_{v_{ij}} - \pi_{v^-_j})^2\right]} \tag{20}$$

The distance calculations here quantify each alternative's deviation from ideal best and worst performances in the context of intuitionistic fuzzy data, taking into account membership, non-membership, and hesitation information.

Step 8. Calculate the Closeness Coefficient and Rank Alternatives

The closeness coefficient CC_i measures how close an alternative is to the positive ideal relative to the negative ideal, integrating the two distances into one score for ranking:

$$CC_i = \frac{S^-_i}{S^*_i + S^-_i} \tag{21}$$

Finally, rank the alternatives in descending order of CC_i. The alternative with the highest CC_i value is identified as the most preferred option.

3. Application of the proposed assessment framework to coastal protection in Golden Coast, Tainan, Taiwan

3.1. Selected coastal region overview

The Golden Coast beach in Tainan City, Taiwan, serves as a significant recreational area, providing entertainment for tourists and residents. Beyond its recreational value, it offers crucial coastal protection for local inhabitants against extreme events, particularly typhoons that frequently occur during summer season in Taiwan. This beach spans approximately 6.4 km, extending from the northern Anping Harbor southward to the Erren River, as shown in Fig. 5. Since the harbor was constructed, the northern part of the beach has experienced significant sediment accumulation, while the southern portion has undergone progressive erosion. Measurements from Sixth River Management Bureau, Water Resources Agency indicate that the coastline in the northern section has advanced from 177.2 m away from the seawall in 2002 to 315.3 m in 2014. In contrast, the southern section has suffered dramatic retreat, with the distance between the coastline and the seawall decreasing from 62.2 m to just 2.3 m over the same period. This is demonstrated by the field photographs in Fig. 6, showing the initial beach condition in 2000 (a), severe erosion in 2012 (b), and the current state in 2025 (c). It can be observed that the beach appears to have recovered in recent years due to annual beach nourishment, but erosion issues still persist. Additionally, these shoreline changes can be observed in satellite images, as reported in the study (Chang et al., 2018). This trend highlights a serious erosion problem affecting the southern part of the Golden Coast.

An offshore observation pile is located at coordinates 22°56′37″N, 120°8′10″E, equipped with an InterOcean S-4 ADW to measure wind, wave, and current conditions. This observation pile is operated by the Institute of Transportation (IOT), Ministry of Transportation and Communications (MOTC), Taiwan. The monthly statistics of wind, wave, and current measurements are also calculated and provided by the center. The statistical results of monthly mean and maximum values for significant wave height H_s, 10-minute average wind speed U_{10}, and current speed U_c are presented in Table 2. The monthly mean values of wind speed, wave height, and current velocity are generally higher during the winter months, indicating stronger seasonal forcing. In contrast, the maximum values of these parameters tend to occur in the summer, which can be attributed to the influence of typhoons. The passage of a typhoon consistently results in significant alterations to the local morphology, thereby contributing significantly to the erosion problem observed in the southern Golden Coast.

In response to the severe erosion along the southern section of the Golden Coast, the local Water Resources Agency implemented a series of hard engineering interventions designed to interrupt sediment transport and promote localized sand accumulation. Vertical groins were constructed in 2010 and 2013, representing a conventional structural approach to address the critical shoreline retreat. These perpendicular coastal structures were strategically positioned to intercept the

Table 2
Monthly mean and maximum values of significant wave height (H_s), 10-minute average wind speed (U_{10}), and current speed (U_c).

	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
Mean H_s [m]	1999–2015	1.45	1.32	1.13	0.82	0.63	0.62	0.59	0.60	0.94	1.27	1.24	1.45	0.98
Max H_s [m]	1999–2015	5.03	4.61	4.98	4.34	3.68	3.73	6.94	6.49	6.08	8.75	5.97	5.53	8.75
Mean U_{10} [m/s]	2009–2015	5.1	4.7	4.4	3.8	3.4	3.8	3.5	3.6	3.3	3.8	3.9	5.0	4.0
Max U_{10} [m/s]	2009–2015	14.0	12.5	14.7	12.9	13.7	18.3	20.5	35.1	24.7	13.4	12.6	15.4	35.1
Mean U_c [m/s]	1999–2015	18.7	18.0	17.9	17.9	19.0	23.2	26.5	28.2	25.2	24.2	20.5	20.0	21.5
Max U_c [m/s]	1999–2015	74.1	76.9	67.1	69.7	86.5	94.0	130.7	147.3	144.1	95.7	82.1	74.0	147.3

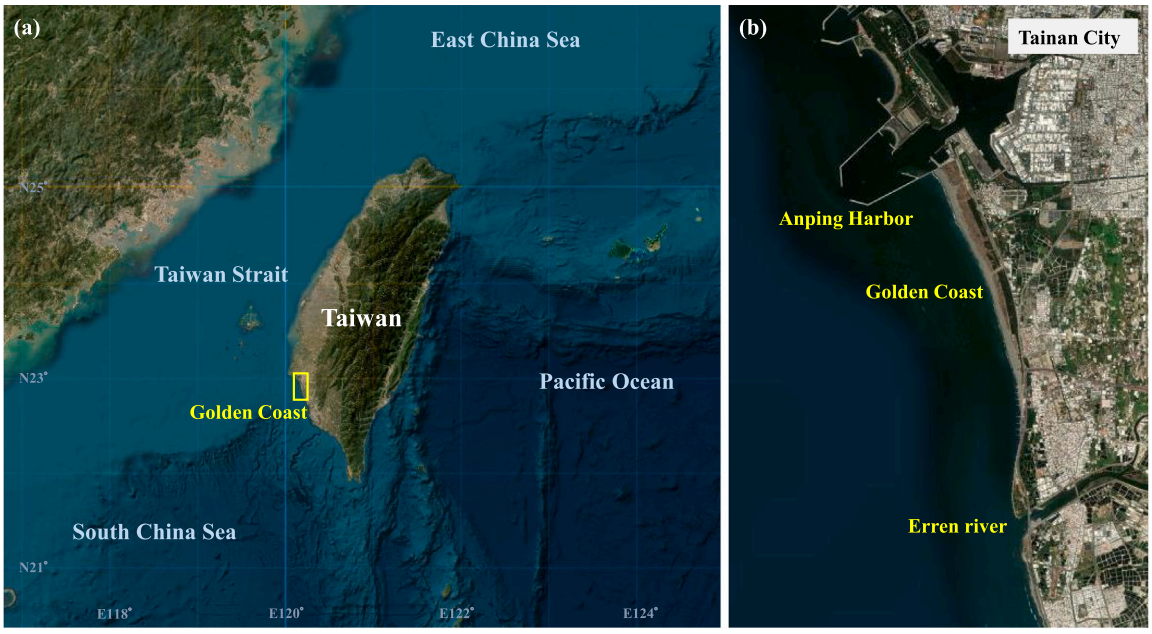


Fig. 5. Location of the study area. (a) Geographic location of the Golden Coast in southern Taiwan. (b) View of the Golden Coast in Tainan City.



Fig. 6. Golden coast southern section with groin structures: (a) February 2000, (b) February 2012, and (c) February 2025. (Sources: (a,b) MOTC report; (c) China Times).

prevailing northward longshore sediment transport, creating sediment traps that theoretically restore beach width. The construction of additional groins temporarily mitigated erosion along the southern Golden Coast. However, this intervention merely displaced erosional pressures to adjacent coastal regions. Consequently, the consideration of NbS remains an essential strategy under active evaluation by Water Resources Agency, Taiwan. Our study further demonstrates a assessment for selecting optimal NbS interventions specifically for this case.

3.2. Application of the proposed method in Golden Coast, Tainan, Taiwan

3.2.1. FDM analysis

In this section, we follow the flowchart of the NbS assessment framework and apply it to the selected case. Data collection for this study was conducted in two stages. In the first stage, FDM was used to gather input from 10 experts via a questionnaire. In the second stage, a IF-TOPSIS survey was distributed to 3 additional experts who are directly involved in the co-implementation and co-management of golden coast shore protection projects. The information of the expert data is shown in Table 3.

Through the literature review, 63 evaluation indicators were identified. These indicators are categorized into nine key societal challenge areas to evaluate the multifaceted impacts of NbS, as shown in Table 4. These categories are: (1) Contribution of NbS to Climate Resilience, addressing the ability to reduce vulnerability to climate related hazards; (2) Water Management, focusing on improving water quality and sustainable hydrological processes; (3) Green Space Management, which includes enhancing and conserving urban biodiversity and natural habitats; (4) Air Quality, emphasizing the role of NbS in pollutant

Table 3
Expert basic information.

Method	Job	Number of people	Gender/Number	Education level/Number	Year of experience
FDM	Academic researcher	3	Male/2; Female/1	Doctor/3	10, 25, 22
	Government representatives	3	Male/1; Female/2	Doctor/1; Master/1; Bachelor/1	27, 17, 5
	NGO specialists	2	Male/1; Female/1	Master/2	24, 27
	Local stakeholders	2	Male/2	Bachelor/1; High School/1	25, 32
IF-TOPSIS	Academic researcher	1	Male/1	Doctor/1	24
	Government representatives	1	Male/1	Doctor/1	28
	Consulting Engineer	1	Male/1	Master/1	15

removal and improving atmospheric conditions; (5) Urban Regeneration, reflecting revitalization through land use changes and improved public spaces; (6) Participatory Planning and Governance, involving citizen engagement and adaptive management strategies; (7) Social Justice and Social Cohesion, relating to inclusion, equity, and strengthened community ties; (8) Public Health and Well-being, covering both physical and mental health benefits from natural environments; and (9) Potential for Economic Opportunities and Green Jobs, capturing the economic value generated through NbS such as employment and tourism. This classification enables a holistic evaluation of NbS impacts across environmental, social, and economic dimensions.

Based on the 63 evaluation indicators, a questionnaire for the FDM was developed. 10 experts including academic researchers, government representatives, NGO ecosystem specialists, and local stakeholders were formally invited to participate in the survey. This multi stakeholder expert panel ensures coverage of technical, policy, ecological, and implementation perspectives essential for NbS evaluation. Each evaluation indicator was assessed using a Likert scale from 0 to 10, where 0 represents "least important" and 10 represents "most important". Each expert was asked to assign a pessimistic cognitive value, an optimistic cognitive value, and a personal perceived value to each indicator. Following the steps, triangular fuzzy numbers were constructed for each indicator. Subsequently, the gray area analysis was conducted to evaluate the level of agreement among experts and determine the consensus values. The results of this process are presented in Table 4. Evaluation indicators with a consensus value (G^i) greater than 6 were retained.

The evaluation process resulted in 18 consensus indicators selected from the original 63 candidates. These 18 indicators include: Capacity to reduce hydro-meteorological disasters, Number of people at risk, Total area of restored/created wetlands, Ecological status of surface water bodies, Total leaf area index, Accessibility of green spaces, Proportion of land covered by green spaces, Distribution of public green spaces, Area of habitat restored, Natural environment affected by construction, Residents affected by construction, Construction costs, Locally tailored design, Frequency of space use, Permitted recreational space, Recreational value, Perceived sense of safety, and Tourism opportunities. These 18 consensus indicators were subsequently used in the IF-TOPSIS analysis to determine the final ranking of NbS measures.

3.2.2. IF-TOPSIS analysis

In the previous FDM analysis, we engaged a panel of 10 experts with extensive theoretical knowledge and backgrounds in coastal protection to determine the indicator weights. However, the subsequent IF-TOPSIS evaluation required input from practitioners with direct experience in the real-world performance of coastal protection alternatives. To enhance practical accuracy of the assessment, we selected an additional 3 experts with specialized knowledge of the Golden Coast region and its engineering structures. These additional experts included: an engineer with practical experience constructing coastal protection structures in the Golden Coast, a government project manager responsible for planning coastal protection initiatives in the area, an academic specializing in hydrodynamics and morphological changes relevant to coastal environments. All three experts completed the questionnaires for the IF-TOPSIS analysis, ensuring that the evaluation incorporated both broad theoretical insights and localized, practical expertise.

Following the identification of 18 consensus evaluation indicators through the FDM, an IF-TOPSIS approach was adopted to systematically evaluate and rank 18 NbS for coastal protection. The analysis implemented a IF-TOPSIS procedure, enabling the integration of expert knowledge while addressing uncertainty and hesitancy in multi-criteria decision-making. In intuitionistic fuzzy set theory, each element is characterized by three distinct components: membership degree (μ), non-membership degree (ν), and hesitancy degree (π), where $\mu+\nu+\pi = 1$ and all values are constrained to the interval [0, 1]. To facilitate expert assessments, linguistic variables were employed to translate qualitative expert judgments into quantitative intuitionistic fuzzy numbers (Cables et al., 2012; Daneshvar Rouyendegh et al., 2018). The linguistic scale adopted in this study encompasses terms ranging from 'Extremely poor' through 'Neutral' to 'Extremely good', each corresponding to specific intuitionistic fuzzy numbers with predetermined membership, non-membership, and hesitancy values, as shown in Table 5. Experts assessed the 18 NbS measures using the 18 indicators and a shared linguistic scale, organized into expert specific decision matrices.

In Step 2, expert weights were calculated using the entropy method. This step ensured that evaluations from experts with greater certainty and lower informational entropy were given relatively more influence in subsequent aggregation. In Step 3, the intuitionistic fuzzy Weighted Averaging (IFWA) operator was applied to aggregate individual expert evaluations into consensus values. This process incorporated the expert weights, ensuring that more reliable expert judgments had a greater influence on the final consensus matrix. Due to the large size of the matrix, only a fragment of the integrated decision matrix is presented, specifically, indicator 1 from expert 1, as shown in Table 6. These entropy values are then transformed into objective indicators, yielding the attribute weights. Based on the derived attribute weights, the intuitionistic fuzzy decision matrix was constructed and subsequently normalized, as shown in Table 7. Due to the large size of the decision matrices in Tables 6 and 7, the full tables are included in the supplementary material. The attribute weights reveal that our investigation emphasizes the environmental dimension, as evidenced by the substantial weights assigned to "Area of habitat restored", "Capacity to reduce hydro-meteorological disasters", and "Total area of restored/created wetlands". In contrast, social dimensions such as "Residents affected by construction" and "Permitted recreational space", along with the economic dimension of "Tourism opportunities", received the lowest weights. However, the high weight assigned to "Perceived sense of safety" demonstrates that social dimensions are also valued, particularly as safety directly relates to coastal protection effectiveness. This emphasis on safety is especially relevant in Taiwan local environments, where extreme atmospheric conditions from typhoons may induce significant coastal hazards. Using the weighted normalized matrix, the intuitionistic fuzzy positive ideal solution A^* and negative ideal solution A^- were determined, as shown in Table 8. Subsequently, the normalized Euclidean distances from each alternative to the positive ideal solution S_i^* and to the negative ideal solution S_i^- were computed. Finally, the closeness coefficient CC_i was obtained for each alternative,

Table 4
Evaluation Indicators for Coastal NbS.

Evaluation Indicator	C_i^L	C_i^M	C_i^U	O_i^L	O_i^M	O_i^U	M_i	Z_i	$M_i - Z_i$	G_i	Screening result
Climate resilience and mitigation											
Capacity to reduce hydro-meteorological disasters	3	4.62	7	9	9.29	10	4.7	−2	6.67	6.95	○
Total carbon removed/stored by vegetation/soil/sediment	2	2.96	5	7	7.37	9	4.4	−2	6.41	5.18	×
Avoided greenhouse gas emissions	3	3.80	6	7	7.57	9	3.8	−1	4.78	5.85	×
Urban heat island incidence	2	2.70	6	5	7.13	9	4.4	1	3.43	5.39	×
Direct and indirect losses caused by hazards	2	3.65	6	7	7.56	9	3.9	−1	4.91	5.60	×
Risk to infrastructure	3	3.75	5	7	7.94	9	4.2	−2	6.19	5.85	×
Number of people at risk	3	3.92	5	7	8.36	9	4.4	−2	6.44	6.14	○
Productive areas at risk	3	3.75	5	7	7.95	9	4.2	−2	6.20	5.85	×
Roads at risk	3	3.27	4	6	7.63	9	4.4	−2	6.36	5.45	×
Water Management											
Improvement in water quality	2	3.57	7	8	8.07	9	4.5	0	4.54	5.82	×
Total area of restored/created wetlands	4	4.61	7	8	8.88	10	4.3	−1	5.28	6.75	○
Infiltration capacity	3	3.34	5	7	7.57	9	4.2	−2	6.23	5.48	×
Evapotranspiration rate	3	3.08	5	7	7.68	9	4.6	−2	6.59	5.38	×
Total wetland area	3	4.25	7	6	7.57	8	3.3	1	2.32	5.91	×
Ecological status of surface water bodies	3	4.28	7	8	8.77	10	4.5	−1	5.49	6.53	○
Green Space Management											
Total leaf area index	2	3.68	6	8	8.67	10	5.0	−2	6.98	6.18	○
Accessibility of green spaces	3	3.92	5	7	8.36	10	4.4	−2	6.44	6.14	○
Proportion of land covered by green spaces	3	3.84	5	7	8.36	10	4.5	−2	6.53	6.10	○
Distribution of public green spaces	3	3.84	5	7	8.03	10	4.2	−2	6.20	5.94	×
Diversity of green spaces	3	4.02	6	7	9.14	10	5.1	−1	6.12	6.58	○
Amount of invasive alien species	2	3.19	7	7	8.06	9	4.9	0	4.87	5.62	×
Proportion of natural areas	2	3.14	6	7	7.99	9	4.8	−1	5.85	5.56	×
Area of habitat restored	1	4.02	6	8	8.59	9	4.6	−2	6.56	6.30	○
Proportion of biodiversity conservation areas	1	3.17	6	7	8.04	9	4.9	−1	5.87	5.61	×
Potentially hazardous animal species	1	3.08	6	6	7.98	10	4.9	0	4.90	5.53	×
Accessibility of NbS	3	3.75	5	7	8.24	10	4.5	−2	6.49	6.00	×
Natural environment affected by construction	3	3.95	5	7	8.28	9	4.3	−2	6.33	6.11	○
Air Quality											
Amount of atmospheric pollution removed by vegetation	1	2.58	6	7	7.95	9	5.4	−1	6.37	5.26	×
Air quality index value	2	3.12	6	6	7.74	9	4.6	0	4.62	5.43	×
Exposure to noise pollution	1	2.63	4	5	7.75	10	5.1	−1	6.13	5.19	×
Urban Regeneration											
Wasteland reclaimed for NbS	2	3.31	5	7	7.37	9	4.1	−2	6.07	5.34	×
Area expansion	2	2.91	5	6	7.83	9	4.9	−1	5.92	5.37	×
Created landscapes	2	3.31	5	7	8.14	10	4.8	−2	6.84	5.72	×
Residents affected by construction	3	3.95	5	7	8.26	9	4.3	−2	6.31	6.11	○
Construction costs	4	4.45	6	7	8.05	10	3.6	−1	4.59	6.25	○
Participatory Planning and Governance											
Citizen participation	1	2.70	5	7	7.94	10	5.2	−2	7.24	5.32	×
Social learning	1	2.38	5	7	7.56	9	5.2	−2	7.18	4.97	×
Proportion of citizens involved in participatory processes	2	2.93	4	7	7.47	9	4.5	−3	7.54	5.20	×
Development of new policies	1	1.99	5	7	7.74	10	5.8	−2	7.76	4.87	×
Participation of traditionally underrepresented groups	1	2.26	4	6	7.37	8	5.1	−2	7.11	4.81	×
Adjustment of local plans and regulations	1	2.48	5	7	7.76	10	5.3	−2	7.28	5.12	×
Interaction among social groups	1	2.27	5	6	7.83	10	5.6	−1	6.56	5.05	×
Inclusion and respect	1	2.61	5	6	7.80	10	5.5	−1	6.19	5.20	×
Participation in volunteer service	1	1.80	5	5	7.27	9	5.2	0	5.47	4.54	×
Social Justice and Social Cohesion											
Sense of place identity	3	3.62	5	7	8.35	10	4.7	−2	6.73	5.99	×
Locally tailored design	3	3.73	5	7	8.53	10	4.8	−2	6.80	6.13	○
Pro-environmental behavior	2	3.33	6	7	7.96	10	4.6	−1	5.64	5.65	×
Attitudes triggered by contact with NbS	1	2.22	5	6	7.08	8	4.9	−1	5.86	4.65	×
Accessibility for people with disabilities	1	2.58	5	5	7.53	10	4.9	0	4.95	5.05	×
Public Health and Well-being											
Frequency of space use	3	4.23	6	7	9.35	10	5.1	−1	6.12	6.79	○
Permitted recreational space	3	4.00	6	6	8.90	10	4.9	0	4.90	6.45	○
Visual assessment	2	3.07	4	6	7.83	10	4.8	−2	6.76	5.45	×
Recreational value	3	3.84	5	6	8.81	10	5.0	−1	5.97	6.32	○
Perceived sense of safety	3	4.18	7	8	8.76	10	4.6	−1	5.58	6.47	○
Perceived chronic stress	1	2.11	4	5	6.81	8	4.7	−1	5.70	4.46	×
Visual perception of NbS	2	2.60	4	7	7.76	10	5.2	−3	8.16	5.18	×
Economic Opportunities and Green Jobs											
Direct economic activity (retail and commercial)	3	3.44	5	6	8.14	10	4.7	−1	5.70	5.79	×
Tourism opportunities	3	3.98	5	5	8.54	10	4.6	0	4.57	6.29	○
Changes in property income	1	1.99	5	5	7.13	10	5.1	0	5.14	4.56	×
Economic value of nature	1	2.49	4	6	7.42	9	4.9	−2	6.93	4.95	×
Change in property prices	1	2.31	5	5	7.21	10	4.9	0	4.90	4.76	×
Regional profitability	1	2.48	5	6	8.01	10	5.5	−1	6.53	5.24	×
Number of jobs created	2	3.05	5	6	8.22	10	5.2	−1	6.17	5.64	×

Table 5
Linguistic terms for rating the alternatives.

Linguistic terms	IFNs
Extremely good	[0.9, 0.1, 0]
Very good	[0.8, 0.1, 0.1]
Good	[0.7, 0.2, 0.1]
Slightly good	[0.6, 0.3, 0.1]
Neutral	[0.5, 0.4, 0.1]
Slightly poor	[0.4, 0.5, 0.1]
Poor	[0.25, 0.6, 0.15]
Very poor	[0.1, 0.75, 0.15]
Extremely poor	[0.1, 0.9, 0]

representing its relative proximity to the ideal solution. These coefficients served as the basis for the final ranking of alternatives, also shown in Table 9. The complete tables of Tables 6 and 7 are provided in the supplementary material.

Table 9 presents the final ranking of the 18 NbS measures for coastal protection in the Golden Coast, Tainan, Taiwan. The results reveal that mangroves achieved the highest closeness coefficient (CC_i = 0.8316), followed by salt marsh (CC_i = 0.7562), coral reef (CC_i = 0.6705), living breakwater (CC_i = 0.6507), and buffer zone (CC_i = 0.6502). The closeness coefficient effectively highlights the discriminative power of the IF-TOPSIS approach in differentiating among NbS alternatives based on expert assessments.

Our results provide actionable recommendations for government policymakers and coastal engineers involved in the ongoing Golden Coast coastal protection project in Tainan. The current management strategy, which relies primarily on the installation of groins and annual beach nourishment, has shown limited effectiveness. While erosion has slightly decreased, it continues to affect the beach. The final ranking provides a evaluation and serves as a valuable reference for guiding subsequent project planning. From an engineering perspective, the recommended solutions prioritize NbS structures and will be further developed into different scenarios, supported by hydrodynamic numerical models to assess feasibility and by cost–benefit analysis to compare effectiveness in planning. Numerical modeling in this stage can assess the performance of NbS measures under extreme conditions as well as to predict morphological changes that contribute to their long term coastal protection effectiveness. For our project, we are currently in the ongoing process of sharing our results with Taiwan's Water Resources Agency to suggest implementing the prioritized NbS measures as solutions to existing coastal protection strategies at the Golden Coast site.

3.3. Discussion of limitations and future applications

The proposed framework provides an multi-criteria decision analysis for selecting 18 NbS measures in coastal protection. However,

Table 6
Results of IF-TOPSIS from Step 1 to Step 3.

	NbS measures	$\left[D_{m1}^{(1)}\right]_{m=1}^{18}$	$\left[w_{m1}^{(1)}\right]_{m=1}^{18}$	$\left[D'_{m1}\right]_{m=1}^{18}$
NbS1	Mangrove	[0.80, 0.10, 0.10]	0.333	[0.80, 0.10, 0.10]
NbS2	Salt marsh	[0.70, 0.20, 0.10]	0.441	[0.68, 0.22, 0.10]
NbS3	Seagrass	[0.70, 0.20, 0.10]	0.441	[0.68, 0.22, 0.10]
NbS4	Dune	[0.70, 0.20, 0.10]	0.512	[0.64, 0.26, 0.10]
NbS5	Coral reef	[0.70, 0.20, 0.10]	0.308	[0.74, 0.15, 0.10]
NbS6	Oyster reef	[0.70, 0.20, 0.10]	0.333	[0.70, 0.20, 0.10]
NbS7	Beach nourishment	[0.80, 0.10, 0.10]	0.333	[0.80, 0.10, 0.10]
NbS8	Buffer zone	[0.70, 0.20, 0.10]	0.333	[0.70, 0.20, 0.10]
NbS9	Living breakwater	[0.80, 0.10, 0.10]	0.333	[0.80, 0.10, 0.10]
NbS10	Artificial reef	[0.80, 0.10, 0.10]	0.333	[0.80, 0.10, 0.10]
NbS11	Permeable pile groins	[0.70, 0.20, 0.10]	0.372	[0.68, 0.22, 0.10]
NbS12	Gravity drainage	[0.70, 0.20, 0.10]	0.333	[0.70, 0.20, 0.10]
NbS13	Geotextile tube	[0.80, 0.10, 0.10]	0.392	[0.77, 0.13, 0.11]
NbS14	Artificial headland	[0.50, 0.40, 0.10]	0.333	[0.50, 0.40, 0.10]
NbS15	Sand fence	[0.50, 0.40, 0.10]	0.219	[0.56, 0.34, 0.10]
NbS16	Artificial floating island	[0.80, 0.10, 0.10]	0.357	[0.78, 0.12, 0.10]
NbS17	Natural wave breaker	[0.80, 0.10, 0.10]	0.333	[0.80, 0.10, 0.10]
NbS18	Eco-friendly wave breaker	[0.80, 0.10, 0.10]	0.333	[0.80, 0.10, 0.10]

Table 7
Results of IF-TOPSIS from Step 4 to Step 5.

	Evaluation indicators	W_j		NbS measures	$\left[V_{m1}\right]_{m=1}^{18}$
I1	Capacity to reduce hydro-meteorological disasters	0.0568	NbS1	Mangrove	[0.0454, 0.0057, 0.0057]
I2	Number of people at risk	0.0550	NbS2	Salt marsh	[0.0387, 0.0123, 0.0058]
I3	Total area of restored/created wetlands	0.0565	NbS3	Seagrass	[0.0387, 0.0123, 0.0058]
I4	Ecological status of surface water bodies	0.0558	NbS4	Dune	[0.0361, 0.0148, 0.0059]
I5	Total leaf area index	0.0555	NbS5	Coral reef	[0.0422, 0.0087, 0.0059]
I6	Accessibility of green spaces	0.0550	NbS6	Oyster reef	[0.0397, 0.0114, 0.0057]
I7	Proportion of land covered by green spaces	0.0551	NbS7	Beach nourishment	[0.0454, 0.0057, 0.0057]
I8	Distribution of public green spaces	0.0551	NbS8	Buffer zone	[0.0397, 0.0114, 0.0057]
I9	Area of habitat restored	0.0577	NbS9	Living breakwater	[0.0454, 0.0057, 0.0057]
I10	Natural environment affected by construction	0.0555	NbS10	Artificial reef	[0.0454, 0.0057, 0.0057]
I11	Residents affected by construction	0.0544	NbS11	Permeable pile groins	[0.0384, 0.0126, 0.0057]
I12	Construction costs	0.0558	NbS12	Gravity drainage	[0.0397, 0.0114, 0.0057]
I13	Locally tailored design	0.0555	NbS13	Geotextile tube	[0.0436, 0.0072, 0.0060]
I14	Frequency of space use	0.0551	NbS14	Artificial headland	[0.0284, 0.0227, 0.0057]
I15	Permitted recreational space	0.0544	NbS15	Sand fence	[0.0317, 0.0193, 0.0057]
I16	Recreational value	0.0551	NbS16	Artificial floating island	[0.0440, 0.0069, 0.0058]
I17	Perceived sense of safety	0.0569	NbS17	Natural wave breaker	[0.0454, 0.0057, 0.0057]
I18	Tourism opportunities	0.0548	NbS18	Eco-friendly wave breaker	[0.0454, 0.0057, 0.0057]

Table 8
Results of IF-TOPSIS for Step 6.

	Evaluation indicators	Positive ideal solution A^*	Negative ideal solution A^-
I1	Capacity to reduce hydro-meteorological disasters	[0.0454, 0.0057, 0.0057]	[0.0284, 0.0227, 0.0060]
I2	Number of people at risk	[0.0355, 0.0139, 0.0055]	[0.0231, 0.0251, 0.0068]
I3	Total area of restored/created wetlands	[0.0477, 0.0057, 0.0010]	[0.0141, 0.0339, 0.0085]
I4	Ecological status of surface water bodies	[0.0463, 0.0067, 0.0016]	[0.0191, 0.0296, 0.0081]
I5	Total leaf area index	[0.0487, 0.0056, 0.0013]	[0.0139, 0.0333, 0.0083]
I6	Accessibility of green spaces	[0.0430, 0.0063, 0.0055]	[0.0241, 0.0242, 0.0073]
I7	Proportion of land covered by green spaces	[0.0457, 0.0067, 0.0026]	[0.0202, 0.0279, 0.0107]
I8	Distribution of public green spaces	[0.0457, 0.0067, 0.0010]	[0.0127, 0.0351, 0.0076]
I9	Area of habitat restored	[0.0487, 0.0058, 0.0005]	[0.0262, 0.0245, 0.0076]
I10	Natural environment affected by construction	[0.0411, 0.0084, 0.0055]	[0.0277, 0.0222, 0.0073]
I11	Residents affected by construction	[0.0404, 0.0082, 0.0055]	[0.0195, 0.0280, 0.0069]
I12	Construction costs	[0.0415, 0.0086, 0.0056]	[0.0262, 0.0241, 0.0068]
I13	Locally tailored design	[0.0409, 0.0084, 0.0056]	[0.0300, 0.0198, 0.0070]
I14	Frequency of space use	[0.0431, 0.0063, 0.0055]	[0.0250, 0.0237, 0.0068]
I15	Permitted recreational space	[0.0422, 0.0066, 0.0054]	[0.0199, 0.0276, 0.0079]
I16	Recreational value	[0.0457, 0.0067, 0.0027]	[0.0250, 0.0234, 0.0073]
I17	Perceived sense of safety	[0.0479, 0.0066, 0.0010]	[0.0306, 0.0203, 0.0083]
I18	Tourism opportunities	[0.0454, 0.0064, 0.0027]	[0.0138, 0.0337, 0.0080]

Table 9
Results of IF-TOPSIS from Step 7 to Step 8.

	NbS measures	S_i^*	S_i^-	CC_i	Ranking
NbS1	Mangrove	0.0041	0.0202	0.8316	1
NbS2	Salt marsh	0.0059	0.0183	0.7562	2
NbS3	Seagrass	0.0097	0.0171	0.6391	7
NbS4	Dune	0.0092	0.0151	0.6211	9
NbS5	Coral reef	0.0083	0.0168	0.6705	3
NbS6	Oyster reef	0.0095	0.0149	0.6105	10
NbS7	Beach nourishment	0.0086	0.0157	0.6455	6
NbS8	Buffer zone	0.0083	0.0155	0.6502	5
NbS9	Living breakwater	0.0087	0.0162	0.6507	4
NbS10	Artificial reef	0.0090	0.0151	0.6248	8
NbS11	Permeable pile groins	0.0127	0.0111	0.4675	13
NbS12	Gravity drainage	0.0153	0.0106	0.4082	15
NbS13	Geotextile tube	0.0153	0.0095	0.3830	16
NbS14	Artificial headland	0.0135	0.0109	0.4465	14
NbS15	Sand fence	0.0100	0.0155	0.6071	11
NbS16	Artificial floating island	0.0121	0.0131	0.5197	12
NbS17	Natural wave breaker	0.0171	0.0101	0.3714	17
NbS18	Eco-friendly wave breaker	0.0172	0.0096	0.3573	18

several limitations should be acknowledged. First, the evaluation relies heavily on expert judgments, which may still reflect individual biases and project familiarity. In future studies, carefully defined inclusion criteria for selecting experts could help reduce such biases and improve the robustness of the assessment.

Second, the current framework only provides the ranking of NbS measures but does not explicitly address the potential for combining multiple NbS measures (e.g., mangroves with living breakwaters) to address complex coastal problems. These interactions can be investigated through laboratory experiments and field implementations to assess the functional performance of combined NbS measures and identify interaction effects that yield the highest efficiency.

Third, the proposed framework is applied here to a single case study based on the Gold Coast in Tainan, Taiwan. The 18 consensus indicators obtained from the FDM may differ when applied to other sites. Additionally, different sites may be suitable for different NbS measures, which requires more case studies to further improve our proposed framework. However, this requires various participants to provide their feedback to further enhance stakeholder engagement and co-design, thereby strengthening the co-creation, co-implementation, and co-management of NbS projects.

4. Conclusion

The growing global adoption of nature-based solutions (NbS) to replace traditional gray infrastructure for coastal protection is driven by increasing awareness of climate change impacts, accumulating evidence of cost-effectiveness, and supportive policy frameworks. Successful implementation of NbS projects requires on-site co-creation, co-implementation, and co-management across diverse climatic and socio-economic contexts with the active participation of engineers and all other stakeholders (Ferreira et al., 2023; Ghosh et al., 2024; Dushkova and Kuhlicke, 2024). Nevertheless, systematic approaches to assess the effectiveness of NbS in coastal protection remain limited. This study fills that gap by introducing a assessment framework that integrates the Fuzzy Delphi Method (FDM) and entropy-based intuitionistic fuzzy TOPSIS (IF-TOPSIS) to evaluate and rank coastal protection measures across diverse evaluation indicators. This combined approach is particularly effective for evaluating emerging environmental projects and novel technologies, where data are sparse and expert-driven insights are critical (Nguyen, 2022).

Our study identified 18 coastal protection measures, ranging from purely natural solutions to hybrid structures, and applied a assessment framework through a case study on the Golden Coast, Tainan, Taiwan. By engaging stakeholders including coastal engineers, ecologists, policymakers, and community representatives, we utilized the FDM to refine an initial pool of 63 evaluation indicators into 18 consensus indicators spanning nine societal challenge domains. These served as the basis for constructing the decision matrix for IF-TOPSIS, which then enabled systematic evaluation and ranking of the 18 measures. The results revealed that mangroves achieved the highest closeness coefficient ($CC_i = 0.8316$), establishing them as the most suitable

nature-based solution for coastal protection in this case. The complete ranking identifies the top five coastal protection measures as: (1) mangroves, (2) salt marshes, (3) coral reefs, (4) living breakwaters, and (5) buffer zones. The case study demonstrates and validates the applicability of the proposed framework for coastal protection. Meanwhile, we suggest that the framework is generalizable and can be adapted to other cases, offering valuable support for developing more effective coastal protection strategies.

From an engineering perspective, the framework enables practitioners to quantify trade-offs between coastal structural performance and ecosystem co-benefits in decision-making. Nevertheless, the current approach relies heavily on the professional knowledge of experts (engineers, government project managers, and academic researchers) to provide scoring for the IF-TOPSIS method. Although this study concentrates on assessing NbS measures, the effective realization of such projects demands additional stages, including planning, implementation, monitoring, and governance, all of which require the collaborative involvement of diverse stakeholders.

CRediT authorship contribution statement

Dong-Jiing Doong: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yu-Chen Lee:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Fröhle:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Zoran Vojinovic:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Cheng-Hui Liao:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dong-Jiing Doong reports financial support was provided by National Science and Technology Council. If there are other authors, they 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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Appendix A. An overview of 18 nature-based solutions for coastal protection

By a systematic overview of the literature, we provide an overview of 18 distinct NbS measures applicable to diverse coastal environments, providing a foundational understanding before applying to our proposed framework. Table A.10 lists the NbS structures for coastal protection and the related studies referenced in this study.

Mangrove

Mangroves play a crucial role in coastal protection by acting as natural barriers that reduce the impacts of storms, flooding, and erosion on vulnerable shorelines. Their dense root systems dissipate wave energy, trap sediments, and stabilize coastlines, thereby decreasing the risk of property damage and loss of life during extreme weather events (Barbier et al., 2011; Bao, 2011; Gedan et al., 2011). Numerous studies have demonstrated that mangrove forests can significantly reduce wave heights and storm surges, with wide and healthy mangrove belts providing the greatest protective benefits (Beck and Lange, 2016; Narayan et al., 2016). The effectiveness and cost-efficiency of mangroves as nature-based coastal defenses have led to growing interest in their conservation and restoration, not only for disaster risk reduction but also for supporting livelihoods and biodiversity (Van Coppenolle et al., 2018). Several case studies have already demonstrated the effectiveness of mangroves for coastal protection in different cities (Mahmood et al., 2023; Gomes et al., 2025; Jayson-Quashigah et al., 2025).

Salt marsh

Salt marshes are vital coastal ecosystems that provide significant protection against erosion, flooding, and storm surges. Their dense vegetation and sediment trapping capacity enable them to dissipate wave energy and stabilize shorelines, thereby reducing the impacts of extreme weather events and sea level rise (Barbier et al., 2011; Gedan et al., 2011; Li et al., 2024; Rupprecht et al., 2017). Research has shown that salt marshes can attenuate up to 72% of wave energy during storm surges, highlighting their effectiveness as natural buffers for coastal defense (Narayan et al., 2016). Beyond their protective function, salt marshes contribute to ecosystem resilience and offer additional benefits such as carbon sequestration and habitat provision, making them an essential component of sustainable coastal management strategies (Van Coppenolle et al., 2018). In the Ems Estuary, a joint Netherlands and Germany case study examined the use of constructed salt marshes to protect coastal wetlands Baptist et al. (2021).

Seagrass

Seagrass is increasingly recognized for their important role in coastal protection, providing natural defense against erosion, flooding, and wave action. Through their dense underwater vegetation and extensive root systems, seagrasses stabilize sediments, reduce water turbidity, and attenuate wave energy, thereby minimizing shoreline erosion and supporting coastal resilience (Barbier et al., 2011; Bouma et al., 2014; Ondiviela et al., 2014). The effectiveness of seagrass in mitigating coastal hazards depends on factors such as meadow density, species composition, and local hydrodynamic conditions with denser and healthier meadows offering greater protective benefits (Ondiviela et al., 2014; Bouma et al., 2014). As the need for sustainable and nature-based coastal defense solutions grows, seagrass restoration and conservation are increasingly promoted as complementary or alternative strategies to traditional hard infrastructure, offering both ecological and socio-economic co-benefits (Chen et al., 2022; Schoonees et al., 2019). A case study in the Wadden Sea area of the German Bight demonstrates that seagrass could be a useful addition to engineered coastal protection measures (Jacob et al., 2023; Castrillón et al., 2025).

Dune

Coastal dunes are dynamic landforms that serve as natural barriers against storm surges, coastal erosion, and flooding. By accumulating and stabilizing sand through wind action and vegetation, dunes provide a flexible and self-repairing buffer that protects inland areas from the impacts of extreme weather events and sea level rise (Doody, 2012; Hanley et al., 2014). The effectiveness of dunes in coastal defense is enhanced by the presence of native vegetation, which helps bind sand and maintain dune structure, while human interventions such as dune restoration and management can further strengthen their protective role (Doody, 2012; Roscoe and Diermanse, 2011). Beyond their physical protection, dunes also offer valuable ecosystem services, supporting biodiversity and recreational opportunities, and their conservation is increasingly recognized as a cost-effective and sustainable approach to coastal management (Barbier et al., 2011; Hanley et al., 2014). Field experiences at beaches have proven that dunes can stabilize the coast

Table A.10
NbS structures for coastal protection with selected references from the literature.

No.	Measures	References
1	Mangrove	Barbier et al. (2011), Bao (2011), Gedan et al. (2011), Beck and Lange (2016), Narayan et al. (2016), Van Coppenolle et al. (2018)
2	Salt marsh	Barbier et al. (2011), Gedan et al. (2011), Narayan et al. (2016), Rupprecht et al. (2017), Best et al. (2018), Van Coppenolle et al. (2018), Chowdhury et al. (2019), Li et al. (2024)
3	Seagrass	Barbier et al. (2011), Bouma et al. (2014), Ondiviela et al. (2014), Schoonees et al. (2019), Chen et al. (2022)
4	Dune	Barbier et al. (2011), Roscoe and Diermanse (2011), Doody (2012), Hanley et al. (2014)
5	Coral reef	Barbier et al. (2011), Ferrario et al. (2014), Quataert et al. (2015), Beck and Lange (2016), Narayan et al. (2016)
6	Oyster reef	Bouma et al. (2014), Narayan et al. (2016), Chowdhury et al. (2019)
7	Beach nourishment	Hanley et al. (2014), Chen et al. (2022), Kindeberg et al. (2023), Geukes et al. (2024)
8	Buffer zone	Tamburrino et al. (2020), Lan and Hsu (2021), Kwon et al. (2024)
9	Living breakwater	Moosavi (2017), Baker et al. (2018), Fotopoulos et al. (2025), Kazakis et al. (2025)
10	Artificial reef	Harris (2009), López et al. (2016), De Almeida (2017), Mendoza et al. (2019)
11	Permeable pile groins	Poff et al. (2004), Zhang and Stive (2019), Lima et al. (2020), Zhang et al. (2023)
12	Gravity drainage	Katoh and Yanagishima (1996), Kanazawa et al. (1996), Fischione et al. (2022)
13	Geotextile tube	Koerner and Koerner (2006), Oh and Shin (2006), Shin and Oh (2007), Lee et al. (2014), Tayade et al. (2015)
14	Artificial headland	Klein et al. (2010), Goodwin et al. (2013), Vieira da Silva et al. (2017), Pan et al. (2018)
15	Sand fence	Grafals-Soto (2012), Harris et al. (2020), Itzkin et al. (2020), Eichmanns et al. (2021)
16	Artificial floating island	Ware and Callaway (2019), Ware (2020), Landmann et al. (2022), Raju and Arockiasamy (2022)
17	Natural wave breaker	Dionne (2002), Schmitt and Albers (2014), Chowdhury et al. (2019)
18	Eco-friendly wave breaker	Firth et al. (2014), Ido and Shimrit (2015), Martínez et al. (2022), Zhao et al. (2024)

and enrich coastal vegetation (González-Villanueva et al., 2023; White et al., 2024; Sedrati et al., 2025).

Coral reef

Coral reefs are among the most effective natural barriers for coastal protection, providing substantial defense against wave action, erosion, and flooding. Their complex structures dissipate up to 97% of incoming wave energy, with the reef crest alone responsible for the majority of this attenuation, thereby reducing the risk of coastal hazards for millions of people living in tropical coastal zones (Ferrario et al., 2014; Beck and Lange, 2016; Nonaka et al., 2024). Comparative analyses show that coral reefs can deliver wave attenuation benefits similar to or greater than artificial structures like breakwaters, and restoration of reefs is often more cost-effective than building such engineered defenses (Barbier et al., 2011; Ferrario et al., 2014). Furthermore, coral reefs are highly effective at reducing wave heights, especially in high energy environments, and their capacity for self-repair enhances their long term value as a nature-based solution for coastal risk reduction (Narayan et al., 2016; Quataert et al., 2015). As threats to coral reefs from climate change and other pressures increase, their conservation and restoration are increasingly recognized as essential strategies for safeguarding coastal communities and infrastructure (Beck and Lange, 2016; Narayan et al., 2016). After reef restoration, field studies have demonstrated that coral reefs assist in mitigating coastal erosion for coastal protection (Brathwaite et al., 2022; Toth et al., 2023; Storlazzi et al., 2025).

Oyster reef

Oyster reefs are increasingly recognized as valuable natural infrastructure for coastal protection, functioning as biogenic breakwaters that attenuate wave energy, reduce shoreline erosion, and stabilize sediments (Bouma et al., 2014; Narayan et al., 2016; Chowdhury et al., 2019). These living structures can dynamically adapt to changing sea levels and environmental conditions, offering a resilient alternative to traditional hard engineering solutions (Bouma et al., 2014; Chowdhury et al., 2019). In addition to their protective role, oyster reefs enhance local biodiversity by providing habitat for a wide range of marine species and supporting fisheries, thereby delivering important ecological and socio-economic benefits (Chowdhury et al., 2019). The restoration and strategic placement of oyster reefs have been shown to significantly reduce wave heights and promote coastal resilience, making them a promising nature-based solution for safeguarding vulnerable shorelines (Narayan et al., 2016; Chowdhury et al., 2019). Studies of restored native oyster reefs at field sites have demonstrated cost-effectiveness and coastal defense functions, providing a valuable solution for coastal protection (Scyphers et al., 2011; Hynes et al., 2022; Shinn et al., 2025).

Beach nourishment

Beach nourishment is a widely adopted coastal protection strategy that involves the addition of sand to beaches and nearshore environments to counteract erosion and enhance shoreline stability. This approach works by supplementing the natural sediment budget, thereby maintaining or widening beaches and dunes, which serve as buffers against storm surges and wave action (Hanley et al., 2014; Geukes et al., 2024). Compared to hard engineering solutions, beach nourishment is considered a flexible, adaptive, and often more environmentally friendly method, as it works with natural coastal processes and can be suited to local conditions (Chen et al., 2022). Innovative large scale projects, such as the Sand Motor in the Netherlands, demonstrate how beach nourishment can provide long term coastal protection while also creating new habitats and recreational spaces (Kindeberg et al., 2023; Geukes et al., 2024). As climate change and rising sea levels increase the risks to coastal areas, beach nourishment is increasingly recognized as a key component of integrated, sustainable coastal management strategies (Chen et al., 2022; Hanley et al., 2014). It has been applied

to the coast demonstrating its ability as an NbS (Chen et al., 2022; Kindeberg et al., 2023; Geukes et al., 2024).

Buffer zone

Buffer zones are strategically designated areas along coastlines that serve to reduce the impacts of coastal hazards by providing a protective barrier between human activities and sensitive natural environments. These zones help mitigate erosion, absorb floodwaters, and filter pollutants before they reach marine and freshwater systems, thereby enhancing the ecological resilience and safety of coastal regions (Tamburrino et al., 2020; Lan and Hsu, 2021). The effectiveness of buffer zones in coastal protection depends on careful planning, functional zoning, and adaptive management that consider local environmental conditions and land use pressures (Lan and Hsu, 2021; Kwon et al., 2024). Recent research emphasizes the importance of integrating ecological restoration and sustainable land management within buffer zones to maximize their protective and multifunctional benefits for both people and ecosystems (Tamburrino et al., 2020; Kwon et al., 2024). Some studies on sites also have provided evidence of the significance of coastal buffer zones (Lan and Hsu, 2021; Kwon et al., 2024; Lee et al., 2025).

Living breakwater

Living breakwaters are innovative coastal protection structures that combine traditional engineering with ecological enhancement to reduce wave energy, control erosion, and provide habitat for marine life (Moosavi, 2017; Baker et al., 2018). Unlike conventional hard breakwaters, living breakwaters are designed to support ecological functions such as reef ridges, tide pools, and habitat spaces for oysters and other marine organisms, thereby increasing both coastal resilience and biodiversity (Moosavi, 2017; Baker et al., 2018). Numerical and physical modeling studies have demonstrated that living breakwaters effectively attenuate wave energy and can be optimized to perform under both typical and extreme storm conditions (Baker et al., 2018; Fotopoulos et al., 2025). Recent research also highlights the multifunctional benefits of living breakwaters, including their adaptability to changing sea levels and their role in fostering social and ecological connectivity along the shoreline (Moosavi, 2017; Kazakis et al., 2025). It has shown that living breakwaters are increasingly recognized as a sustainable nature-based solution for coastal protection in the face of climate change through on-site structures (Sayar et al., 2025).

Artificial reef

Artificial reefs are engineered structures placed on the seabed to mimic the protective functions of natural reefs, providing coastal defense by dissipating wave energy and stabilizing shorelines (Harris, 2009; De Almeida, 2017). These multifunctional reefs act as submerged breakwaters, reducing wave and current impacts, beach erosion and promoting shoreline accretion while simultaneously enhancing marine habitats and biodiversity (Harris, 2009; López et al., 2016; Zhang et al., 2024). Advances in artificial reef design, such as modular and eco-friendly materials, have improved their effectiveness and adaptability to local environmental conditions, making them valuable tools in integrated coastal management (López et al., 2016; Mendoza et al., 2019). Beyond physical protection, artificial reefs offer additional benefits, including supporting recreational activities and fisheries, thus delivering ecological, social, and economic value to coastal communities (De Almeida, 2017; Mendoza et al., 2019). It is beginning to attract some countries to implement them on-site (Dauvin and Foveau, 2019; Apriani et al., 2022).

Permeable pile groins

Permeable pile groins are specialized coastal protection structures designed to stabilize beaches and counteract erosion by partially intercepting longshore sediment transport while allowing some flow of water and sediment through their open framework (Poff et al., 2004; Zhang and Stive, 2019). Unlike impermeable groins, which can cause significant downdrift erosion by completely blocking littoral drift, permeable pile groins constructed from rows of slender piles promote a more balanced sediment distribution and maintain a straighter shoreline profile (Zhang and Stive, 2019; Zhang et al., 2023). Numerical and experimental studies have shown that these structures effectively reduce longshore current velocities within groin fields and can be optimized through careful design of their spacing, length, and permeability to maximize beach stabilization benefits (Lima et al., 2020; Zhang et al., 2023). As a result, permeable pile groins are increasingly recognized as a flexible and adaptive solution for sustainable coastal management, offering protection while minimizing negative impacts on sediment dynamics and adjacent shorelines, and have been demonstrated on site (Poff et al., 2004).

Gravity drainage

Gravity drainage is an innovative coastal protection technique that involves installing a permeable layer beneath the beach surface to naturally lower the groundwater table and reduce beach erosion during storms (Katoh and Yanagishima, 1996; Kanazawa et al., 1996). By facilitating the seaward drainage of groundwater, this system helps stabilize the beach profile, minimizes sediment loss, and preserves the natural appearance of the shoreline, as most components are buried underground and remain unobtrusive to beach users (Kanazawa et al., 1996). Experimental and field studies have shown that gravity drainage can effectively prevent the rise in groundwater level and wave setup during storm events, thereby increasing the critical wave height required to initiate foreshore erosion and slowing the rate of beach retreat compared to untreated beaches (Katoh and Yanagishima, 1996; Kanazawa et al., 1996; Fischione et al., 2022). While gravity drainage offers a soft and environmentally sensitive approach to shoreline stabilization, its success depends on site specific factors such as sediment permeability and local hydrodynamics, and it is generally considered most effective under moderate wave conditions (Fischione et al., 2022).

Geotextile tube

Geotextile tubes are innovative, soft engineering structures used for coastal protection, offering an effective and economical alternative to traditional hard defenses such as rock revetments and seawalls (Koerner and Koerner, 2006; Shin and Oh, 2007; Lee et al., 2014). Constructed from high strength, permeable geotextile fabrics and filled with sand or dredged material, these tubular barriers can be deployed as submerged breakwaters, revetments, or embankments to dissipate wave energy, reduce shoreline erosion, and promote natural sediment accumulation (Oh and Shin, 2006; Shin and Oh, 2007). Their adaptability, ease of installation, and lower environmental impact make geotextile tubes particularly suitable for locations where natural rock is scarce or where rapid, cost-effective coastal protection is needed (Koerner and Koerner, 2006; Lee et al., 2014). Additionally, geotextile tubes can be integrated with other materials, such as gabions, to enhance durability and wave energy dissipation, further extending their application in diverse coastal environments (Tayade et al., 2015; Shin and Oh, 2007).

Artificial headland

Artificial headlands are engineered coastal structures designed to mimic the natural protrusions of headlands, with the primary goal of stabilizing shorelines, promoting sediment accumulation, and reducing coastal erosion (Klein et al., 2010; Goodwin et al., 2013). By altering local wave patterns and sediment transport processes, artificial headlands help create and maintain pocket beaches, which are embayed stretches of shoreline sheltered from direct wave attack and thus more resistant to erosive forces (Vieira da Silva et al., 2017; Pan et al., 2018). Comparative studies have shown that artificial headlands can effectively replicate the morphodynamic behavior of natural headlands, supporting beach stability and providing long term coastal protection when properly designed and integrated into broader coastal management strategies (Klein et al., 2010; Pan et al., 2018). Their performance depends on factors such as headland spacing, orientation, and local

Table B.11
Questionnaires for the FDM.

Evaluation of Key Indicators for Nature-based Solutions in Coastal Protection Using the Fuzzy Delphi Method

Thank you for taking the time to support our research. Please read this questionnaire carefully and indicate whether each listed indicator is important for nature-based solutions (NbS) in coastal protection. The results will be used solely for academic research. All personal information will remain strictly confidential.				
Information	Gender: Age: Education level: Experience in industry/ academia: Job title:			
Category		Climate resilience and mitigation		
Indicator		**Capacity to reduce hydro-meteorological disasters**		
	Does this indicator influence NbS in coastal protection? Yes ☐; No ☐	If yes, please indicate the degree of influence on a scale from 0 (small) to 10 (large). Pessimistic Cognitive Value	Optimistic Cognitive Value	Personal Perceived Value
Score		☐	☐	☐
Indicator		**Number of people at risk**		
	Does this indicator influence NbS in coastal protection? Yes ☐; No ☐	If yes, please indicate the degree of influence on a scale from 0 (small) to 10 (large). Pessimistic Cognitive Value	Optimistic Cognitive Value	Personal Perceived Value
Score		☐	☐	☐
Only a subset of the full questionnaire is shown here for brevity				

sediment dynamics, making site specific assessment and design essential for maximizing their protective benefits (Goodwin et al., 2013; Vieira da Silva et al., 2017).

Sand fence

Sand fences are a widely used, nature-based solution for coastal protection, primarily designed to reduce wind velocity at the ground surface and promote the accumulation of sand, thereby facilitating the growth and stabilization of coastal dunes (Grafals-Soto, 2012; Itzkin et al., 2020; Eichmanns et al., 2021). By trapping wind blown sand, these simple structures help initiate and reinforce dune formation, which acts as a natural barrier against coastal erosion and storm surges (Harris et al., 2020; Eichmanns et al., 2021). The effectiveness of sand fences depends on design parameters such as height and porosity and on their placement relative to prevailing winds and existing dune systems (Itzkin et al., 2020; Eichmanns et al., 2021). While sand fences are cost-effective and easy to install, their long term success is maximized when combined with dune vegetation and regular maintenance to ensure sustained protection and ecological benefits (Grafals-Soto, 2012; Harris et al., 2020).

Artificial floating island

Artificial floating islands are an emerging technology for coastal protection, designed to provide both ecological and engineering benefits in response to shoreline erosion and habitat loss. Constructed from buoyant materials such as recycled plastics and polyurethane foam, these islands can be vegetated to support plant growth and create habitats for birds, fish, and invertebrates, while also serving as barriers that absorb wave energy and reduce coastal erosion (Ware and Callaway, 2019; Ware, 2020). Their modular design allows for flexibility in size and application, making them suitable for a variety of coastal environments and adaptable to fluctuating water levels (Landmann et al., 2022). Artificial floating islands can also enhance water quality by supporting microbial communities that filter pollutants, functioning similarly to natural wetlands. As interest in their use grows, it is important to address public concerns related to long term maintenance, potential plastic pollution, and ecological impacts to ensure their successful integration into coastal management strategies (Ware and Callaway, 2019; Raju and Arockiasamy, 2022).

Natural wave breaker

Natural wave breakers, such as boulder fields and oyster reefs, play a significant role in coastal protection by dissipating wave energy and stabilizing shorelines. Boulder accumulations along coastlines can act as robust, passive barriers that absorb and reduce the force of incoming waves, thereby minimizing erosion and safeguarding coastal landforms (Dionne, 2002; Schmitt and Albers, 2014). Similarly, oyster reefs function as living breakwaters; their complex, elevated structures attenuate wave energy, trap sediments, and foster the development of stable intertidal and subtidal zones. Beyond their physical protective benefits, oyster reefs also enhance local biodiversity and provide valuable ecosystem services, making them an effective and sustainable solution for nature-based coastal defense (Chowdhury et al., 2019).

Eco-friendly wave breaker

Eco-friendly wave breakers are innovative coastal protection structures designed to reduce wave energy and shoreline erosion while minimizing negative impacts on marine ecosystems. Unlike traditional hard infrastructure, these wave breakers often incorporate features that enhance habitat complexity and promote biodiversity, such as textured surfaces, cavities, or integration with living organisms like shellfish or seaweeds (Firth et al., 2014; Ido and Shimrit, 2015). Recent studies indicate that eco-friendly wave breakers made from sustainable materials can dissipate wave energy and provide protection comparable to conventional structures while supporting ecological functions and habitat provision (Martínez et al., 2022; Zhao et al., 2024). By balancing engineering performance with environmental benefits, eco-friendly wave breakers represent a promising approach for sustainable coastal management in the face of climate change and increasing coastal development (Firth et al., 2014; Ido and Shimrit, 2015; Martínez et al., 2022).

Appendix B. Questionnaires for the FDM and IF-TOPSIS

The evaluation of NbS for coastal protection at specific sites is conducted following our proposed assessment framework. This evaluation requires the use of two distinct questionnaires, which are specifically

Table B.12
Questionnaires for the IF-TOPSIS.

Evaluation of the Importance of Each Indicator for Nature-Based Solutions Using the intuitionistic fuzzy Technique for Order Preference by Similarity to Ideal Solution (IF-TOPSIS)

Thank you for taking the time to support our research. Please read this questionnaire carefully and indicate whether each listed indicator is important for nature-based Solutions in coastal protection, and to what extent. The results will be used exclusively for academic research purposes, and all personal information will be kept strictly confidential.

Information
Gender:
Age:
Education level:
Experience in industry/ academia:
Job title:

Indicator	**Capacity to reduce hydro-meteorological disasters**								
Measures	Extremely good	Very good	Good	Slightly good	Neutral	Slightly poor	Poor	Very poor	Extremely poor
Mangrove	☐	☐	☐	☐	☐	☐	☐	☐	☐
Salt marsh	☐	☐	☐	☐	☐	☐	☐	☐	☐
Seagrass	☐	☐	☐	☐	☐	☐	☐	☐	☐
Dune	☐	☐	☐	☐	☐	☐	☐	☐	☐
Coral Reef	☐	☐	☐	☐	☐	☐	☐	☐	☐
Oyster Reef	☐	☐	☐	☐	☐	☐	☐	☐	☐
Beach nourishment	☐	☐	☐	☐	☐	☐	☐	☐	☐
Buffer Zone	☐	☐	☐	☐	☐	☐	☐	☐	☐
Living breakwater	☐	☐	☐	☐	☐	☐	☐	☐	☐
Artificial reef	☐	☐	☐	☐	☐	☐	☐	☐	☐
Permeable pile groins	☐	☐	☐	☐	☐	☐	☐	☐	☐
Gravity drainage	☐	☐	☐	☐	☐	☐	☐	☐	☐
Geotextile tube	☐	☐	☐	☐	☐	☐	☐	☐	☐
Artificial headland	☐	☐	☐	☐	☐	☐	☐	☐	☐
Sand fence	☐	☐	☐	☐	☐	☐	☐	☐	☐
Artificial floating island	☐	☐	☐	☐	☐	☐	☐	☐	☐
Natural wave breaker	☐	☐	☐	☐	☐	☐	☐	☐	☐
Eco-friendly wave breaker	☐	☐	☐	☐	☐	☐	☐	☐	☐

Only a subset of the full questionnaire is shown here for brevity

designed for the Fuzzy Delphi Method (FDM) and the intuitionistic fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), respectively. Given the comprehensive length of the full instruments, only a representative excerpt of the questionnaires is presented in the following.

Appendix C. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.coastaleng.2026.104988.

Data availability

Data will be made available on request.

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