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REVIEW ARTICLE

ENGINEERING WITH NATURE: A SYSTEMATIC REVIEW, NATURE-BASED SOLUTIONS (NBS) AND HYBRID COASTAL PROTECTION

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ABSTRACT

Coastal communities worldwide are facing increasing threats from climate change induced hazards such as sea-level rise, storm surge and particularly erosion which are having a negative impact on environmental, economic and socio-cultural stability. Traditional hard structure usually gives immediate mitigation to reduce this problem but they often disrupt the ecosystem and paradigm shift towards nature-based solutions (NbS) and hybrid systems receive a positive response around the world. The rapid evolutions of coastal protection strategies are necessary for a comprehensive review to understand the effectiveness, trends and benefits of NbS and hybrid systems. This systematic literature review (SLR) fills these gaps by synthesizing recent studies to guide resilient coastal adaptation in the face of increasing climate challenges. NbS and hybrid systems offer sustainable, resilient coastal protection with hybrid balancing the ecological benefit and structure reliability. A review of 88 articles from 2020 - 2025 from Scopus and ScienceDirect showed the increasing pathway of this research with mainly publication from Europe and Asia. Field studies and numerical modelling revealed NbS effectively reduces erosion and wave energy in moderate conditions while hybrid systems enhance resilience during extreme events and significantly stabilize the shoreline. The hybrid system approaches provide robust, multifunctional solutions and climate goals. These findings advocate for policy reforms, interdisciplinary collaboration and expand research in underrepresented countries/regions to foster equity and sustainable coastal adaptation strategies.

KEYWORDS

Nature-Based Solutions (NBS), Hybrid NBS, Hybrid System, Green-Grey Infrastructure, Soft-Hard Engineering

1. INTRODUCTION

Worldwide 21st century coastal communities are are experiencing continuous threats from climate change hazards, where coastal erosion stands out as one of the most severe impacts with significant negatives on environmental, economic and socio-cultural aspects (Dong et al., 2024; Gellu et al., 2025; Nielsen et al., 2022; Pang et al., 2023; Toimil et al., 2020; Aikins, 2024; Flayou et al., 2021; Paprotny et al., 2020; Perricone et al., 2020; Pouye et al., 2023; Saadon et al., 2020; Shifqa and Gamage, 2024). According to the study, by focusing coastal erosion without coastal protection and adaptation under mean RCP8.5 scenario, the risk of erosion facing coastal communities can increase up to 48% by year 2100 due to climate change momentum in favour of sea-level rise and storm surge (Kirezci et al., 2020).

Coastal adaptation encompasses a range of design strategies that aim at reducing risk from sea level rise, storm surge, flooding and erosion. As revealed six categories for coastal adaptation: i) no response, ii) advance, iii) protection, iv) retreat, v) accommodation and vi) ecosystem-based adaptation (EbA) (Oppenheimer et al., 2019). Each option differs in objectives, measures and socio-ecological implications.

A paradigm shift occurs towards ecosystem-based adaptation (EbA) involve actions that integrate conservation, restoration work with sustainable management of ecosystem to buffer coastal hazards due to previous coastal protection heavily relies on traditional hard structures such as seawall, dikes and revetments. These structure often expensive, ecologically disruptive and transfer risk to adjacent areas through altered sediments dynamics leading the phenomena called “coastal squeeze”.

This study aims to conduct a Systematic Literature Review (SLR) to examine NbS and hybrid coastal protection approaches. The primary objectives of this study are to review the literature on NbS and hybrid coastal protection approaches and to identify trends and performance

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metrics for these systems. Specifically, this SLR seeks to address the following research questions: (1) What are the types and characteristics of nature-based and hybrid coastal protection systems? (2) What are the benefits derived from research on NbS and hybrid coastal protection systems? Through this analysis, the study aims to contribute to a deeper understanding of the effectiveness and potential of these approaches in addressing coastal protection challenges in the context of climate change.

Generally, nature-based solutions (NbS) refer to the usage of natural processes or mimic the ecosystem to address social and economic challenges such as climate change, biodiversity loss, water security and disaster risk. These actions include the protection, management and restoration of modified ecosystems to deliver its benefits for both human-being and biodiversity. Specifically in the context of coastal protection and climate change adaptation, NbS refers to the use of natural ecosystems and designed systems to mimic nature to reduce coastal hazard/risk such as erosion, sea level rise and storm surge. These solutions aim to enhance coastal resilience by stabilizing shoreline naturally, absorbing wave energy and increasing the coastal ability to recover from the disturbance.

There are several widely recognized definitions of NbS from the European Commission, International Union for Conservation of Nature (IUCN), Organization for Economic Cooperation and Development (OECD) and United Nation Environmental Programme (UNEP – 5th United Nation Environmental Assembly).

The European Commission (EC) defines NbS as: > “Solutions that aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature both using and enhancing existing solutions to challenges as well as exploring more novel approaches. NbS utilises the features and complex system processes of nature such as its ability to store carbon and regulate water flows to achieve desired outcomes such as reduced disaster risk and an environment that improves human well-being and promotes socially inclusive green growth” (Europe Commission, 2015).

Later, the International Union for Conservation of Nature (IUCN) defined NbS as: > “Actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefit” (Cohen-Shacham et al., 2016; IUCN, 2020).

Organization for Economic Cooperation and Developments (OECD) define NbS as:> “Measures that protect, sustainably manage and restore nature, to maintain or enhance ecosystem services to address a range of social, environmental and economic challenges” (Denny et al., 2024; OECD, 2021).

United Nation Environment Programme (UNEP) in 5th United Nation Environment Assembly (UNEA – 5) define NbS as:> “Action to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystem which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits” (Denny et al., 2024; UNEP, 2022).

2. METHODS

2.1 Search Strategy

The methodology used in this review was adapted the *systematic (also known as structured) literature review* (SLR) approach, which ensures a focused and structured search process by allowing the review to work closely and align with the research objectives and specific areas of interest, while reducing bias and increasing the transparency of articles (Haddaway et al., 2015; Tranfield et al., 2004). As suggest the usage of systematic review due to its several ability such as synthesis existing knowledge in order to determine whether progress of the certain interest research areas are being made translate into action, identify issues, enable comparison within the interest areas of research, ensure the appropriate resource allocation and can be one of the source for inform stakeholder or governance on currents status or gap of interest of research areas (Bering-Ford et al., 2015).

Systematic searching was run in this review, three sub processes of systematic searching approach were performed namely identification, screening and eligibility.

2.2 Identification

The identification process involves searching for synonyms and variation of main study keywords by enriching the keywords using an online thesaurus. Its purpose is to expand the search in the selected database to retrieve more relevant articles for the review. The searching process was conducted on a selected primary database by using the enriched keywords and keywords used by past studies. Advanced searching technique including using Boolean operator, along with phrase searching and field code function separately or by combining this searching technique into full searching string. Manual searching techniques including handpicking and snowballing were also practiced. To retrieve relevant articles and documents for this review, two main databases namely Scopus and ScienceDirect were selected as primary databases as suggested who confirmed the searching capabilities of these two databases with several advantages such as advanced search functions, comprehensive coverage with indexing over 5,000 publishers, quality control of articles and provide multidisciplinary studies articles (Gusenbauer and Haddaway, 2019). The reason for using two databases is to reduce and minimize potential bias that may occur within a single database as recommended by (Haddaway et al., 2015).

Scopus was chosen because it is recognized as one of the most comprehensive abstract and citation databases of peer-reviewed literature which covers a wide range of multidisciplinary research interests including science, technology, engineering, social science and environmental studies. In addition, Scopus provides advanced search and citation tracking features that enable researchers to identify potential works, monitor research trends and ensure the comprehensive retrieval of relevant studies.

ScienceDirect was included as a complementary primary database to strengthen the searching process. ScienceDirect provides direct access to full-text articles and book chapters published by Elsevier which is one of the leading academic publishers in the field of science and engineering. This database shares significant high-quality publications in coastal engineering, environmental management and nature-based solutions (NbS) research. By including the ScienceDirect database in the searching process, it may help to ensure the keywords work in these domains were captured in full text which may not always be available in other databases (Falagas et al., 2008)

Before finalized, the search string was initially tested in the Scopus and ScienceDirect database, where several variations were compared to ensure that retrieved papers were both relevant and comprehensive. For example, by combining Nature-based Solutions (NbS) with hybrid coastal protection as keywords and enriching keywords in one search string as below:

i) TITLE-ABS-KEY (("engineering with nature" OR "eco-engineering" OR "nature-based engineering" OR "green engineering" OR "sustainable engineering" OR "environmental engineering") AND ("hybrid protection" OR "integrated defense" OR "mixed approach" OR "dual-structures" OR "combined solutions" OR "hard-soft integration") AND ("dune-dike" OR "sand barrier" OR "hybrid dune" OR "coastal dune" OR "dike system") AND ("nature solutions" OR "green infrastructure" OR "ecosystem approach" OR "natural defenses" OR "soft engineering"))

ii) TITLE-ABS-KEY (("engineering with nature") AND ("hybrid coastal protection") AND ("dune-dike system") AND ("nature-based solutions (NBS)"))

Unfortunately, these two search strings do not give any result in returned, zero (0) documents found for Scopus database and show “use fewer boolean connectors (Max 8 per field)” in ScienceDirect. Since both keywords do not give any result in both databases, the author decided to use an alternative style which is a separate search string for both Nature-based Solutions (NbS) and hybrid coastal protection for Scopus database and reduce boolean connector in ScienceDirect advanced search as in Table 1.

Table 1: Finalized and Established Search String (Scopus and ScienceDirect) to identify Literature of Nature-Based Solutions (NbS) and Hybrid Coastal Protection.

Scopus	
Nature-Based Solutions (NbS)	**Hybrid Coastal Protection**
TITLE-ABS-KEY(("nature-based solutions" OR "nature solutions" OR "green infrastructure" OR "ecosystem approach" OR "natural defense" OR "soft engineering") AND ("coastal protection" OR "shoreline defense" OR "coastal defense" OR "beach protection" OR "erosion control" OR " coastal resilience"))	TITLE-ABS-KEY(("hybrid coastal protection" OR "green-grey infrastructure" OR "integrated coastal protection" OR "combined hard and soft engineering" OR "hybrid nature-based solutions (hybrid NbS)" OR "nature engineering synergy" OR "coastal infrastructure resilience"))
ScienceDirect **(Nature-based Solutions + Hybrid Coastal Protection)**	
TITLE, ABSTRACT OR AUTHOR-SPECIFIED KEYWORDS: ("nature-based solutions" OR "ecosystem approach" OR "soft engineering" OR "hybrid coastal protection") AND ("coastal protection" OR "coastal defense" OR "coastal resilience")	

A total of twelve (12) sources were used as supporting databases namely Emerald Insight, Frontiers, ProQuest, DOAJ, ResearchGate, MDPI, Semantic Scholar, Nature, PubMed, Science Advances, Springer Nature Link and Wiley Online Library. These supporting databases were included in this review to capture any missing journals and articles that might not appear in the primary database. Xiao and Watson (2017) mentioned supporting databases needed since no database is comprehensive and perfect. Even though the primary database has an advanced searching function, revealed they still have limitations including low sensitivity towards keywords and restricted search functions (Bates et al., 2017). Thus, this shows that each selected supporting database provides specific advantages. As result in the identification stage a total 720 articles were identified from a combination of two primary databases and twelve supporting databases using the defined search string.

2.3 Screening

This review screened all articles using predefined selection criteria applied through the sorting function available in the chosen databases. In the supporting databases, the articles were excluded manually with the same criteria being applied when sorting functions were not available. In this review the inclusion period was set between 2020 - 2025 since it is impossible for an author to review all existing published articles. As stated the publication timeline should be restricted when the studies were reported within the specific timeline (Higgins and Green, 2011). In this case, previous studies have established that research on coastal protection using nature-based solutions (NbS) and hybrid nature-based solutions has gained momentum in recent years. Therefore, applying this method of restriction is considered appropriate.

In order to ensure the quality of the review, only empirical studies published as journal articles, books and chapters in books were included. In addition, only publications in English were considered to avoid misinterpretation in understanding. Publication before 2020, conference proceedings, newspaper, review paper and non-English sources were excluded. The process excluded 219 articles that did not meet the inclusion criteria and the remaining 501 articles were advanced to the eligibility process. The detailed inclusion and exclusion criteria applied in this review are presented in Table 2.

Table 2: Inclusion and Exclusion Criteria Applied in the Screening Process.

Criteria	**Inclusion**	**Exclusion**
Timeline Publication	2020 to 2025	Before 2020
Publication Type	Article Journal, Book, Chapter in Book	Conference Proceeding, Newspaper, Review Paper
Language	English only	Non-English

2.4 Eligibility

Eligibility is the third stage, in which authors manually assessed the retrieved articles to ensure that those remaining after screening met the predefined criteria. This process involved removing the duplicate, reviewing the title and abstracts, and when relevance articles could not be determined, the content of the articles such as methodology and result were examined. A total of 369 articles were excluded at this stage including duplicate records across databases and the selected articles did not focus on using nature-based solutions (NbS), hybrid nature-based solutions as coastal protection such as urban water logging, river cooling, stormwater treatment/management, urban flood pluvial, water quality, urban stormwater, rainfall scenario, urban water management, urban climate resilience, co-building trust in urban nature, urban green-grey infrastructure, urban catchment, flood mitigation integrated vegetation and non-point pollution control. In total, 132 articles were retained for this stage process. After excluding 44 articles such as unretrievable articles, subscription-based articles and articles behind a paywall, a total 88 articles were retained for further full text review. The systematic search strategy adopted in this review is displayed in Figure 1.

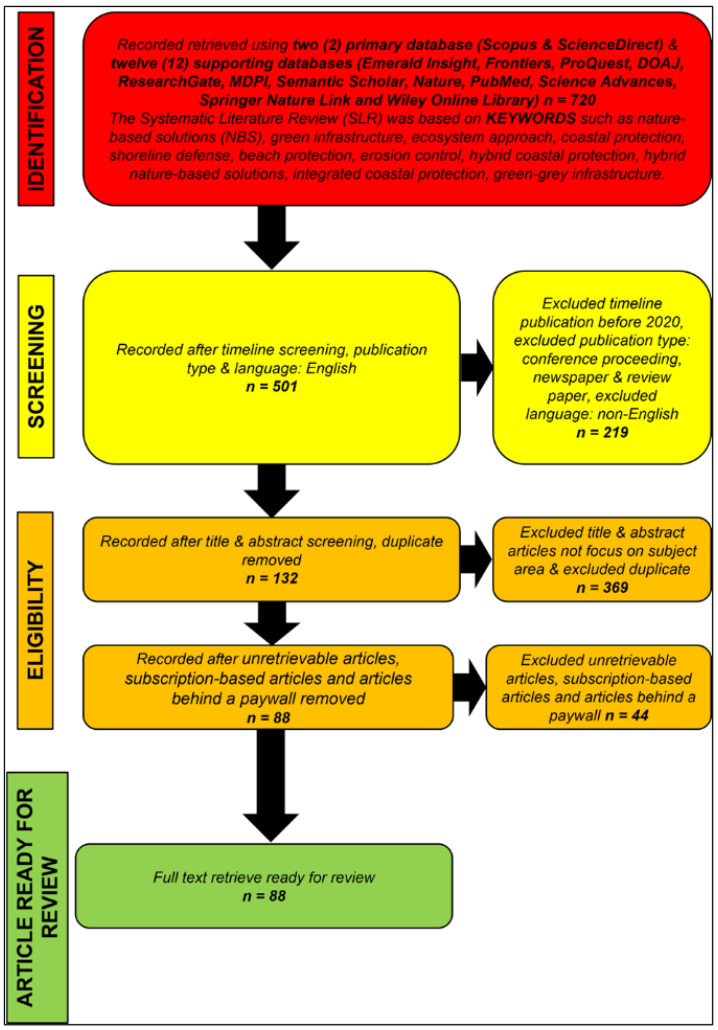

Figure 1: The Flow Diagram of Result for Documents Selection Process.

3. Results

3.1 Publication of Nature-Based Solutions and Hybrid as Coastal Protection

A total of 88 articles were identified in this review. The publication articles on nature-based solution (NbS) and hybrid approaches for coastal protection show the clear upwards trend across the reviewed period within the year 2020 to 2025 as in Figure 2. In 2020, six articles were published, followed by four in 2021. The number increased to 13 in 2020 and slightly decreased to 10 in 2023. A sharp growth was observed in 2024 with 21 publications and the momentum continued in 2025 with 34 articles.

This pattern reflects the growing academic attention and recognition of nature-based solutions (NbS) and hybrid approaches as viable coastal protection recently. Increasing research in this topic indicates that the field has gained momentum and strengthened research agendas towards climate adaptation and coastal management.

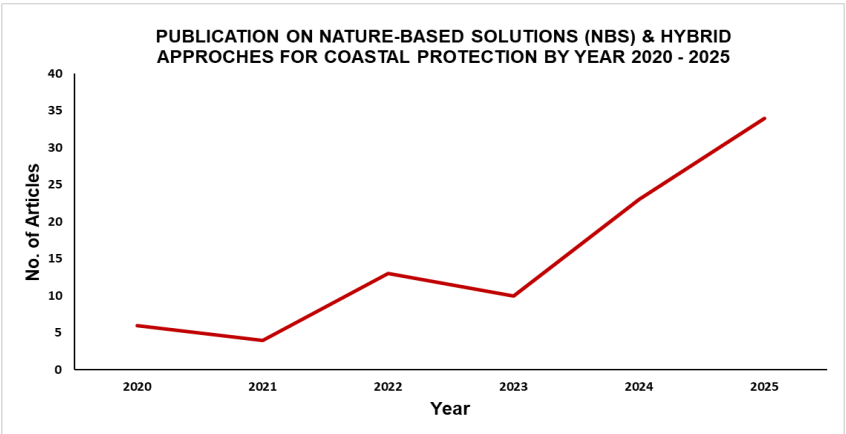

Figure 2: Annual Distribution of 88 Publications on Nature-based Solutions (NbS) and Hybrid approaches for Coastal Protection from 2020 to 2025.

3.2 Geographical Distribution on Nature-Based Solutions (NbS) and Hybrid Approaches for Coastal Protection

The reviewed articles demonstrated a wide range of 32 different countries of geographical distributions on the topic from 2020 to 2025 reveal the diverse global landscape with contributions spanning multiple continents and reflecting a variety level of research activity across nations. This analysis is based on a review of available articles, highlighting the number of publications attributed to each country or region. As shown in Figure 3, a total 104 locations were identified across five continents, the majority originating from Europe. While the review comprised 88 references, the number of countries represented more than the references due to some articles being done in multiple study locations within a single reference.

In terms of publication output, Europe appears as the dominant region

contributing approximately 53.85% of the total publication (56 publications). Germany leads with 14 publications followed by Netherlands (10 publications), United Kingdom (six publications), Belgium (five publications), France, Italy, Portugal (four publications each), Spain (three publications), Ireland (two publications) and Sweden, Finland, Greece (one publication each). This concentration of research may come from robust funding mechanisms that help to establish the research infrastructure, collaborative networks within the European Union and historical focus on coastal engineering and its policy that emphasize the sustainability of coastal management within these nations.

Asia represented the second largest with 25 publications equivalent to 24.04% of total publication. The contributors included Indonesia (five publications), China (four publications), and Iran (three publications). Countries with active research outputs were Bangladesh, Japan, Singapore and Vietnam contributing between two to three publications each. Countries such as India, Malaysia, Maldives, Thailand and Philippines provide a single contribution. The growing research output in this topic across Asia indicates the increasing recognition of the field (NbS) as part of coastal protection strategy in rapidly developing and climate vulnerable regions.

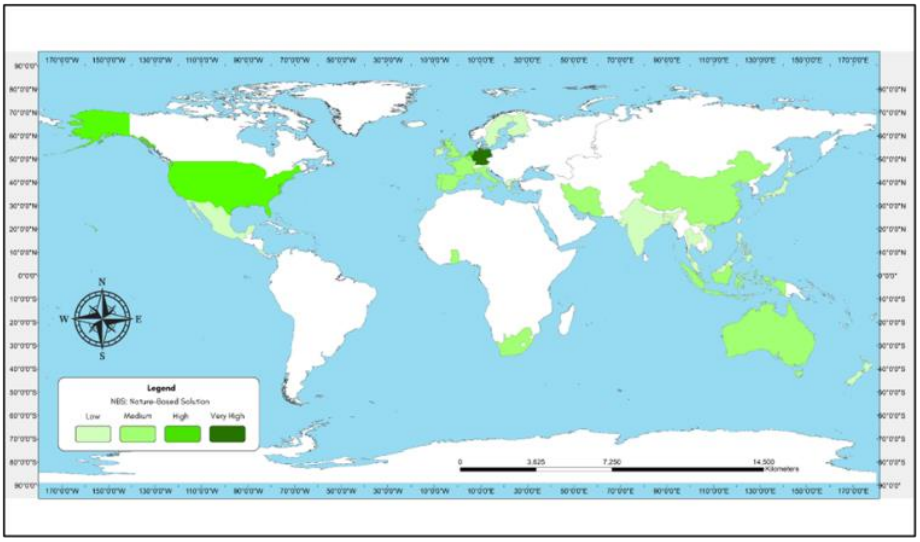

Figure 3: Geographical Distribution of Articles Locations.

North America contributed 13 publications in total with 12.50%, led by the United States with nine publications. Additional contributions originated from the Caribbean Islands (two publications), Costa Rica (one publication) and Mexico (one publication). Oceania contributed with seven publications, mostly coming from Australia (six publications) with minor contributions from New Zealand (one publication). Africa continent recorded the lowest number of contributions with only three publications coming from Ghana (two publications) and one publication from Africa.

As the data shown, the dominant contributor is European countries in this field of research, supported by significant contributions from Asia and North America. The limited knowledge from Africa and Oceania indicates geographical research imbalance between year 2020 to 2025 which is highlighting the need for broader engagement in these regions where the coastal risks are also severe.

3.3 Interdisciplinary Research Areas On Nature-Based Solutions (NbS) and Hybrid Coastal Protection

The distribution of research outputs across journal and publications outlets shows a wide range of disciplinary reflecting interdisciplinary characteristics of NbS and hybrid coastal protection studies. Figure 4 shows the dataset includes 52 identified publications with four major research domains: i) coastal and marine engineering, ii) ecological and environmental sciences, iii) interdisciplinary sustainability and climate change and iv) applied and emerging research themes.

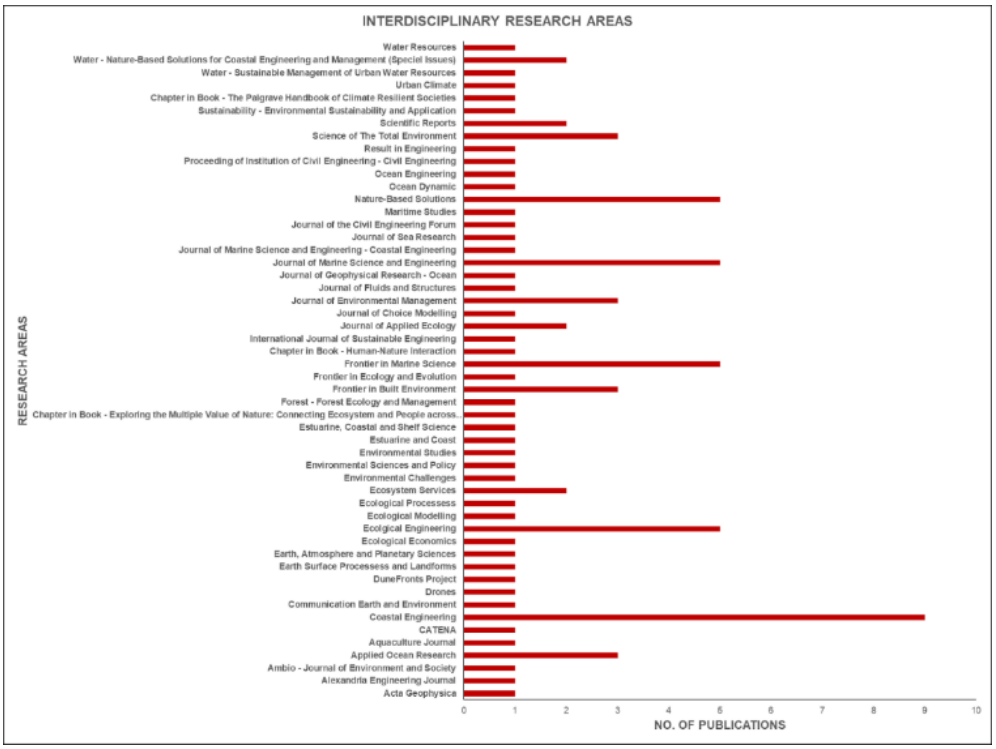

Figure 4: The Interdisciplinary Research Areas Publications on Nature-Based Solutions (NbS) and Hybrid Coastal Protection.

3.3.1 coastal and marine engineering

Engineering journals contributed the largest share of publications. Coastal Engineering recorded the highest number with nine articles, confirming it is central role in advancing technical for coastal protection. Other major contributions come from Ecological Engineering (six articles), Journal of Marine Science and Engineering (five articles), Applied Ocean Research (three articles), Frontiers in Built Environment (three articles) and Ocean Engineering (one article). These contributions reflect a strong emphasis on design, modelling and performance evaluation of hybrid structure as well as integration of natural processes into engineered systems.

3.3.2 ecological and environmental sciences

The second cluster of publication centers on ecological processes, habitat restoration and ecosystem services assessments. Key contributions include Ecological Engineering (five articles), Frontiers in Marine Science (five articles), Scientific Reports (two articles) and Ecosystem Services (two articles). The additional contributions appeared in Journal of Applied Ecology (two articles), Estuarine, Coastal and Shelf Science (one articles) and Ecological Modelling (one articles). These contributions emphasize ecological functions of NbS, biodiversity support and long-term sustainability outcomes.

3.3.3 interdisciplinary sustainability and climate studies

There are a growing number of publications that integrate with social and climate resilience perspectives such as Environmental Science and Policy, Sustainability, Urban Climate, Ecological Economics and Maritime Studies reflect the diversification of research beyond purely technical or ecological dimensions. Each of the journals contributes one publication. The Palgrave Handbook of Climate Resilient Societies and Exploring the Multiple Values of Nature demonstrate the increasing recognition of NbS as relevant solutions for both science and governance.

3.3.4 applied and emerging research themes

Several publications appeared in specialized or emerging research outcomes of experimentation with NbS. Examples in Drones with one article, highlight the technology that enables monitoring the effectiveness of NbS or hybrid coastal protection and Journal of Choice Modelling with also one article, address decision making frameworks for NbS adoption in coastal resilience adaptation as one of their strategies for coastal management. Other contributions from such as Results in Engineering, Environmental Challenges and Communication Earth and Environment suggest that NbS research is expanding and recognised into novel methodological approaches in coastal adaptation.

The distribution shows the dominant research outcome of this topic comes from both engineering and ecological publications. This concentration shows the strong technical and ecological foundations of NbS and hybrid approaches as coastal protection strategies. At the same time, the presence of interdisciplinary sustainability publications and applied research indicates that research is steadily shifting towards more than integrated approaches. This diversity suggests that NbS and hybrid coastal protection is moving beyond proof-of-concept studies towards governance and management discussion by bridging natural science and engineering with socio-economics perspectives.

3.4 Thematic Analysis on Methodologies

In this review, identified five distinct methodologies commonly applied in coastal protection research include conceptual study, field study, numerical modelling, physical modelling and integrated study approaches as shown in Table 3. Each of the methods contribute differently to advance understanding of coastal processes and evaluating protection measures with specific strength and limitations that influence their role in scientific investigation and practical application.

Field study (n = 31) was the most frequently used methodology. This method involves empirical measurement and observation in a natural environment providing strong evidence of coastal dynamics and the effectiveness of protection strategies under real world conditions. The strength of field studies lies in their reliability for validating other approaches as they capture the complexity of coastal systems influenced by climate, geomorphology and human activity. However, they are often limited by scale, cost and time. The finding from this method may not always be generalized to other regions because of the different coastal setting.

Numerical modelling (n = 27) applies computational simulations widely used to simulate, represent and predict coastal processes and assess the performance of protection strategies under different scenarios such as sea-level rise or extreme weather conditions. The main advantages of numerical modelling is its flexibility in exploring future projections and testing multiple scenarios where direct experiment is not accessible. The limitations are on the reliance on assumption, boundary conditions and input data quality which introduces uncertainty, required calibration against empirical data.

Physical modelling (n = 20) relies on scaled laboratory experiments such as wave flumes or hydraulic basins to replicate real coastal environments under controlled conditions. This methodology allows testing of specific variables including wave attenuation and sediments transport which cannot easily be isolated in natural environments. Its strength lies in controlled experimentation and reproducibility. This approach complements field data and numerical models by providing tangible experimental validation. The main limitation of this method is scaling because laboratory conditions cannot fully capture the complexity of coastal systems and reduce the transferability of findings to real-world applications.

Conceptual study (n = 14) focuses on development of theoretical framework, models and hypotheses without direct empirical testing such as comparative between two elements and survey of public perception towards introducing new elements. They provide critical insight into mechanism, relationship and potential approaches that connect engineering with governance, acceptance, social and ecological approach. Their limitations lie in the absence of empirical testing which restricts their direct application in coastal management decisions. Conceptual work is most effective when used as a starting point for more applied research.

Integrated study approaches (n = 7) combined two or more methodologies such as field studies with numerical modelling or physical experiment with conceptual frameworks. This approach leverages the strength of variety methodologies and produces more comprehensive insights into coastal protection strategies. Its strength is in bridging gaps between theory, experimentation and real-world application but it remains less common due to high demand for resources, expertise and interdisciplinary collaboration.

Overall, the findings highlight that field studies remain the dominant methodology in coastal protection research which reflects the continued priority on empirical validations of coastal processes and interventions outcomes. Both numerical and physical modelling provide the extensions point of view by enabling the predictive analysis and controlled experiment, but both require careful calibration and validation against the real-world conditions. As conceptual study less applied in this review, it plays a formative role in advancing to understand the governance, public acceptance, social and ecological for future research trajectories. Although limited in number for integrated study approaches, it represents the most comprehensive pathways in future research as they combine the strength of multiple methodologies while minimizing individual limitations. The balanced balance of these methodologies suggest that the future of coastal protection research lies in more systematic integration of empirical, modelling and conceptual social perspective with diverse interdisciplinary approaches that offer the greatest potential to address the complexity of coastal challenges under changing climatic and socio-environmental conditions.

3.4.1 thematic analysis on hazard reduction

The review identified a wide range of hazards addressed in coastal protection research including coastal erosion, wave attenuation, coastal flooding, climate change, sedimentation, sea level rise, storm surge and hydrodynamic force as tabulated in Table 3.

Coastal erosion (n = 36) was the most frequently addressed hazard. The erosion directly threatens the shoreline, infrastructure and ecosystem. by making it a dominant concern in both engineering and NbS coastal protection. The focus of coastal erosion reflects the measurable impact and its role as a primary driver of coastal vulnerability. The limitations of erosion are highly dependent onsite specific factors which are influenced by geomorphology, sediment supply and human activity which complicates the generalization across different contexts.

Wave attenuation (n =32) was the second most frequently studied hazard that reflects the ability of ecosystems or structures to reduce wave energy before it reaches the shoreline. The strength of this focus is its direct relevance to coastal protection effectiveness. The limitation is that attenuation capacity is diverse with ecological condition, site characteristic and maintenance which makes scaling across regions challenging.

Coastal flooding (n = 11) is often linked to extreme weather events and tidal dynamics which poses risks to coastal communities and infrastructure. Research in this category provides valuable insight of

short-term hazard and disaster risk management where coastal flooding becomes constrained by the unpredictable extreme events due to availability of long-term monitoring datasets.

Climate change (n = 8) typically acts as drivers for multiple coastal hazards such as sea level rise, erosion and flooding. The focus lies in its ability to be contextual for local coastal impacts within the global environmental changes. However, the climate change research always remains broad with less emphasis on site-specific that guide for practical interventions.

Sedimentation (n = 6) influences the coastal morphology and its stability of the protective ecosystem. Research in this area highlights the both benefits of natural sediment deposition and the challenges posed by disruption of sediment supply. Sedimentation is highly dynamic and often depends on riverine and sediment transport processes.

As a long-term hazard, sea level rise (n = 3) consists of the risk of flooding, erosion and saltwater intrusion for the low-lying coastal areas. Research addressing this hazard is crucial for future scenario planning and adaptation due to the effect of this hazard gradually, making it difficult to isolate its impact from other concurrent coastal processes in short-term studies.

Storm surge (n = 2) research highlights the acute impact of extreme meteorological events on coastal systems that lies in recognizing episodic but high impact hazards. The scarcity of the long-term data limited this research which restricted the predictive capacity and limits integration into broader coastal protection planning.

Hydrodynamic force (n = 1) such as wave energy and current velocity are critical for understanding the interaction between coastal protection measures and natural processes. While this study focus provides fundamental insights into physical processes, the limitation lies in the narrow scope and limited practical application when it is studied alone.

Overall, the findings show the coastal erosion and wave attenuation dominate research attention, reflecting their central role in both engineering and ecosystem-based protection strategies. Hazards such as storm surge, hydrodynamic force and sea level rise are less studied despite their growing importance under climate change scenarios. This imbalance suggests a need for broader integration of acute and long-term hazards to support more comprehensive coastal protection planning.

4. Discussion

The result of this review provides a foundation for understanding the current trajectory of coastal protection and management strategies from the synthesis of 88 publications starting 2020 to 2025. This shows the field is undergo transformation and increasing urgency of global response to climate change adaptation strategies. The data suggests that NbS is no longer a niche of ecological concept but has enter the mainstream of coastal protection of engineering. However, the geographical distribution reveals a significant different such as Europe is dominance in this research due to the supported with robust funding and framework while Africa and Oceania region are relatively low. Unfortunely, these regions are often the most vulnerable to climate induced hazards, but they are remains underrepresented in the global research landscaped, highly a critical need for localized studies that accounted the tropical geomorphology and different socio-economic context.

The interdisciplinary nature of the reviewed articles was confirmed coastal protection is a multidisciplinary field that bridging the gap between hydraulic engineering and ecological sciences. The high volumes of publications in journals like *Coastal Engineering* and *Ecological Engineering* suggests the technical design and performance evaluation remain the primary focus. However, the emergence of research in specialized areas such as *Drones* and *Choice Modelling* indicate a maturity of the field where researchers are now looking for innovative ways to monitor effectiveness of the coastal protection. Despite this, the low frequency of "Integrated Study Approaches" indicates that a "silo methodological" still exist. Most studies remain anchored in either pure field of observation or controlled laboratory setting with limited success in merging these into holistic and multi-methodological frameworks that can be easily translated into policy or large-scale construction manuals.

Regarding the hazard address, the finding emphasis on coastal erosion and wave attenuation that suggest that current research is primarily "reactive" to immediate the visible threats. These hazards provide the measurable, short-term data that fits well within typical research cycles. In contrast, long-term or episodic hazards like sea-level rise and storm surges are significantly under-represented. This gap identifies a critical weakness in the current knowledge while we are gaining proficiency in using NbS to manage daily wave energy or coastal hazard. Biggest question for now is our understanding of how these natural and hybrid systems will perform under the extreme condition and pressure of 2050 or 2100 climate scenarios stills remain speculative. Future research must take into an account the priority of longitudinal studies and predictive of numerical modelling to ensure that nature-based interventions are resilient and capable enough to provide the long-term protection against accelerating risks of global climate change.

5. Conclusion

The global research trajectory of NbS and hybrid coastal protection has entered an exponential growth phase and recognition in academic world from 2020 to 2025. The interdisciplinary nature of the field is evidence the strong coverage of coastal engineering and ecological sciences even a recent study id divers into socio-economic and governance theme which is suggesting a mature research agenda. The field studies and numerical modelling remain the primary methodological pillars that provide essential empirical validation and predictive capacity for assessing. From the analysis, it is indicate that while coastal erosion and wave attenuation are well documented, long-term hazards such as sea -level rise and acute storm surge remain critically under-studied. To address this problem, future climate uncertainties research must prioritize multi-hazard assessment and cross-disciplinary collaboration to bridge the gap between technical design and long-term socio-ecological sustainability.

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Author Contribution

The first draft of the manuscript was written by **Muhammad Amirul Syafiq Hamsan** and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Muhammad Amirul Syafiq Hamsan: Writing-original draft, Data curation, Formal analysis, Conceptualization, Methodology, Investigation, Visualization;

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conflict of interest

The authors have declared no conflict of interest regrading the publication of this article.

ethical conduct

Not applicable. All information in this article does not need ethical approval for research or informed consent because human and animal subjects were not involved.

data availability/supplementary data

Not applicable.

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