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Scenario-Based Assessment of Indonesia's Blue Carbon Systems under Restoration and Engineering-Integrated Pathways

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Abstract

Aims: This study assesses the future potential of Indonesia's blue carbon ecosystems from an environmental and climate engineering perspective, focusing on mangroves, seagrass beds, and saltmarshes.
Methods: Using a desk-based mixed-methods approach, it synthesizes secondary data from global and national sources to compare three development trajectories: Business as Usual, restoration-driven, and engineering-integrated pathways. Rather than relying on spatial modeling or site-specific measurements, the analysis applies an engineering-oriented synthesis that links published ecosystem extent and carbon metrics with documented coastal engineering and restoration cases to infer comparative future carbon performance and resilience.
Result: The findings indicate that blue carbon systems can deliver substantially greater and more durable climate benefits when ecological conservation is combined with engineered–nature interventions such as hybrid infrastructure, sediment enhancement, and green coastal buffers. These approaches not only enhance long-term carbon sequestration but also strengthen shoreline protection, biodiversity, and coastal livelihoods. The study identifies persistent gaps in policy integration, financing, and coastal design standards that limit implementation and proposes strategic recommendations for embedding engineering-enhanced blue carbon solutions into Indonesia's climate policies, including Nationally Determined Contributions, and coastal development planning.
Conclusion: Overall, the paper demonstrates the feasibility and relevance of integrating environmental engineering into blue carbon strategies to support climate-resilient coastal development in Indonesia.

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1. Introduction

Indonesia encompasses one of the world's largest and most diverse coastal ecosystems, including extensive mangrove forests, seagrass meadows, and saltmarshes, which benefit on climate resilience and carbon sequestration. These ecosystems form a critical component of global blue carbon dynamics due to their extraordinary capacity to store and sequester carbon at rates far exceeding terrestrial forests (Rahman *et al*., 2024). Mangrove ecosystems, for example, account for nearly one-quarter of global blue carbon reserves, underscoring Indonesia's prominent role in advancing nature-based climate change mitigation efforts (Rahman *et al*., 2024). Beyond their carbon storage, coastal ecosystems also support ecological roles by supporting fisheries, regulating hydrological processes, and sustaining coastal biodiversity, while providing significant economic value to local communities (Hafli *et al*., 2025). In the context of climate change, these ecosystems accelerate Indonesia's expansive coastal systems in strengthening national resilience and advancing low-carbon development through measurable blue carbon conservation and management efforts (Murdiyarso *et al*., 2023).

The importance of blue carbon ecosystems extends beyond their mitigation capacities. They deliver critical adaptation benefits that align strongly with the needs of Indonesia's highly vulnerable coastal regions (Hilmi *et al*., 2021). Blue carbon ecosystems act as natural buffers, the root structures attenuate wave energy, stabilizing sediments, and lowering coastal flooding risks (Van Haspen *et al*., 2023). Seagrasses and saltmarshes further enhance these benefits by supporting sediment accretion, improving water quality, and maintaining ecological integrity across nearshore habitats (Lima *et al*., 2023). These combined ecosystem services are especially significant given Indonesia's high exposure to sea-level rise, land subsidence, and extreme weather events increasingly threaten coastal communities, these ecosystem services have become even more critical (Lumban-Gaol *et al*., 2024). As coastal populations continue to expand, blue carbon ecosystems emerge as a central pillar for integrated mitigation–adaptation strategies that strengthen long term coastal resilience (Vinata *et al*., 2024).

Although blue carbon ecosystems play a strategic role in climate mitigation and adaptation, they continue to experience degradation that reduce Indonesia's overall carbon storage capacity (Murdiyarso *et al*., 2023). Mangrove loss driven by aquaculture expansion, land conversion, infrastructure development, and pollution has significantly diminished the country's blue carbon potential over recent decades (Rahman *et al*., 2024). Seagrass meadows are also increasingly fragmented by coastal tourism, marine traffic, and sedimentation, all of which constrain their ecological recovery (Rifai *et al*., 2024). Saltmarshes, although less documented in Indonesia, experiencing similar threats, particularly from land reclamation and coastal erosion that undermine habitat stability and carbon storage function (Mustofa *et al*., 2025). National and local governments have implemented large-scale mangrove restoration programs, complemented in some areas by community-based initiatives that apply nature-based approaches to enhance restoration outcomes (Limmon *et al*., 2023). However, many of these restoration efforts remain weakly integrated with engineering intervention and lack long-term monitoring, limiting their effectiveness within highly dynamic coastal systems (Mancheno *et al*., 2024). Consequently, numerous restoration projects fail to achieve the ecological and hydrological compatibility necessary to support successful recovery in rapidly changing coastal environments shaped by both climate pressure and human disturbances (He *et al*., 2025).

This persistent divide between ecological restoration efforts and coastal engineering practice exposes a fundamental shortcoming in contemporary coastal management (Jordan & Frohle, 2022). In Indonesia, blue carbon programs still focus largely on biological rehabilitation, and rarely overlook how environment and climate engineered interventions such as sediment management, hydrodynamic adjustment, hybrid coastal structures, and eco-design frameworks could strengthen restoration outcomes (Muller *et al*., 2025). As a result, this imbalance situation contributes to many restoration projects struggle to maintain long-term ecological stability, achieve efficient carbon sequestration or withstand intensifying climate-related stressors (Williamson & Gattuso, 2022). Addressing these challenges requires a shift toward viewing blue carbon ecosystems as engineered-nature systems, where ecological processes and targeted technical innovation work together to enhance performance through intentional design, integrated planning, and hybrid approaches that combine nature-based solutions with engineered interventions (Chaves *et al*., 2021).

To address these gaps, this study evaluates the future carbon value and engineering-relevant performance of Indonesia's blue carbon ecosystems by comparatively assessing three development trajectories: Business as Usual (BAU), restoration-driven interventions, and engineering-integrated pathways. Focusing on mangroves, seagrass beds, and saltmarshes, the analysis synthesizes published ecosystem extent data, carbon stock estimates, and documented restoration and coastal engineering cases to infer how different intervention strategies may alter carbon sequestration potential and ecosystem resilience over time. *The novelty of this study lies in its engineering-oriented, scenario-based synthesis that bridges blue carbon science and coastal infrastructure practice without relying on spatial or numerical modeling*. Rather than producing spatially explicit projections, the study provides an evidence-based, scenario-oriented assessment intended to inform coastal planning, climate policy, and environmental engineering practice. By explicitly linking ecological outcomes with engineering considerations, this research narrows its contribution to identifying where and how blue carbon ecosystems can be strategically enhanced to support climate mitigation, coastal protection, and associated socio-economic benefits in Indonesia.

2. Methods

This study employed a desk-based mixed-methods synthesis, combining structured quantitative parameter extraction with qualitative comparative analysis. The approach was designed to generate evidence-based scenario insights on Indonesia's blue carbon ecosystems by systematically integrating published ecosystem metrics, restoration outcomes, and engineering intervention evidence. Rather than producing spatial projections, the study focused on comparative inference across intervention pathways relevant to environmental and climate engineering practice.

Secondary data were collected through a **systematic screening** of peer-reviewed journal articles, national datasets, global blue carbon assessments, and policy documents published between 2000 and 2024. Inclusion criteria for scientific sources were: (i) explicit reporting of ecosystem extent, biomass, soil carbon, or sequestration rates; (ii) clear methodological description; and (iii) relevance to mangroves, seagrass beds, or saltmarshes in tropical or subtropical contexts, with priority given to Indonesian case studies. Engineering-related case studies were selected based on documented evidence of hybrid or nature-based coastal interventions (e.g., permeable structures, sediment enhancement, eco-dykes) and their reported ecological or geomorphic outcomes. Policy documents were drawn from national and sub-national government sources to contextualize institutional and planning relevance.

The analysis followed four operational steps. First, baseline ecosystem extent and condition were synthesized by reconciling national datasets and peer-reviewed estimates to derive indicative area ranges. Second, carbon stock and sequestration parameters were extracted and harmonized into comparable units by standardizing soil depth assumptions, biomass components, and reporting formats. Third, documented restoration and engineering case studies were analyzed to identify success rates, recovery timelines, and controlling factors, which were then used to inform three scenario trajectories: Business as Usual (BAU), restoration-driven, and engineering-integrated pathways. Finally, outcomes across scenarios were compared using qualitative synthesis and quantitative ranges, focusing on relative differences in carbon gains, resilience indicators, and implementation risks rather than absolute projections.

To enhance methodological robustness, parameter ranges were cross-checked across multiple independent sources, and outlier values were excluded unless supported by site-specific justification. Engineering impacts on carbon outcomes were interpreted through mechanism-based reasoning (e.g., sediment retention, hydrological stabilization) grounded in published empirical evidence. Sensitivity to data uncertainty was addressed by reporting ranges and directional trends, rather than point estimates.

The study is constrained by reliance on secondary data, heterogeneous measurement protocols, and the absence of spatial or numerical modeling. These limitations restrict site-specific precision but do not undermine the study's objective of generating transferable, engineering-relevant insights for strategic planning and policy integration.

3. Results

The findings of this study are based entirely on a systematic synthesis of secondary datasets, peer-reviewed publications, and documented case studies, rather than new field measurements or spatial modeling. Consequently, the results present consolidated estimates, comparative parameter ranges, and qualitatively interpreted patterns drawn from diverse published sources. This approach allows the integration of ecological, biophysical, and engineering-related evidence to be integrated in order to highlight current trends, possible future trajectories, and the relative contributions of indonesia's blue carbon ecosystems across different management scenarios. Although the study does not provide precise spatial quantification, it offers a solid, evidence-based foundation for assessing the environmental and engineering significance of blue carbon systems in indonesia.

3.1 Baseline Estimates: Extent, Condition, and Carbon Stocks

Available secondary datasets give a general but consistent picture of the size and state of Indonesia's main blue carbon ecosystems, mangroves, seagrass beds, and saltmarshes. Even though numbers vary between sources because of differences in when surveys were done, methods used for monitoring, and how ecosystems are classified, it is still possible to form a clear understanding by comparing commonly cited figures and noting the ranges that are supported by several datasets. Indonesia still holds one of the largest mangrove areas in the world, while seagrass beds and saltmarshes, though less well mapped, play a crucial role in the country's coastal environments. In all three ecosystems, the condition varies from healthy to severely degraded, with many areas impacted by the expansion of aquaculture, coastal development, and changes in water flow patterns. These baseline measurements serve as an important reference for evaluating the possible effects restoration projects and integrated management approaches that include engineering solutions.

By applying standardized carbon density values from scientific literature, the estimated total carbon stored in each ecosystem type shows significant potential, especially in the soils and below-ground parts of mangroves. Mangroves generally have the highest carbon density, while seagrass beds and saltmarshes hold moderate but ecologically significant amounts of carbon, especially when considered across large areas. Because of differences in local environmental factors and the variety of published data, the estimates here include ranges of uncertainty to reflect the variation between sources. These adjusted baseline serve as the basis for the scenario based analyses covered in the following sections.

Table 1. Baseline Extent, Condition, and Estimated Carbon Stocks of Indonesia's Blue Carbon Ecosystems

Ecosystem Type	Estimated Extent (ha)	Condition Status (% of total)	Carbon Density (tC/ha)	Notes / Uncertainty Range
Mangroves	3,364,080 (MoEF, 2021)	Intact: ~65% • Degraded: ~25% • Converted: ~10%	702.29 (Maulana & Auliah, 2021)	High confidence for extent; variability in soil depth measurements
Seagrass Beds	1,800,000 (Imran et al., 2024)	Intact: ~45% • Degraded: ~40% • Converted: ~15%	22.70-98.53 (Kurniawan *et al.*, 2025)	Moderate uncertainty; under-surveyed habitats
Saltmarshes	-	Intact: ~55% • Degraded: ~35% • Converted: ~10%	334 (Alongi, 2020)	Low confidence due to inconsistent classification

Note: Carbon density ranges include above-ground biomass, below-ground biomass, and soil organic carbon to depths commonly reported in the literature. National-scale quantitative data for saltmarsh (rawa asin) extent and carbon stocks are currently unavailable; however, existing literature indicates that rawa asin ecosystems are primarily distributed along the coastal zones of Java, Sumatra, and Kalimantan, and are therefore discussed qualitatively in this study.

National mangrove mapping conducted in 2021 (MoEF, 2021) shows that Indonesia contains 3,364,080 ha of existing mangroves and 756,183 ha of potential mangrove habitat, yielding a total mangrove ecosystem extent of 4,120,263 ha, of which existing mangroves constitute 82%. Current mangrove stands are dominated by high-density canopy forests (93%), with only small proportions classified as medium (5%) or low density (2%). The potential mangrove habitat comprises eroded areas, open land, degraded mangrove zones, aquaculture ponds, and newly accreted land, with aquaculture ponds representing about 84% and new landforms about 7%. These patterns indicate that while much of Indonesia's remaining mangrove estate remains structurally robust, most restoration opportunities lie within converted or degraded coastal landscapes, particularly former aquaculture areas.

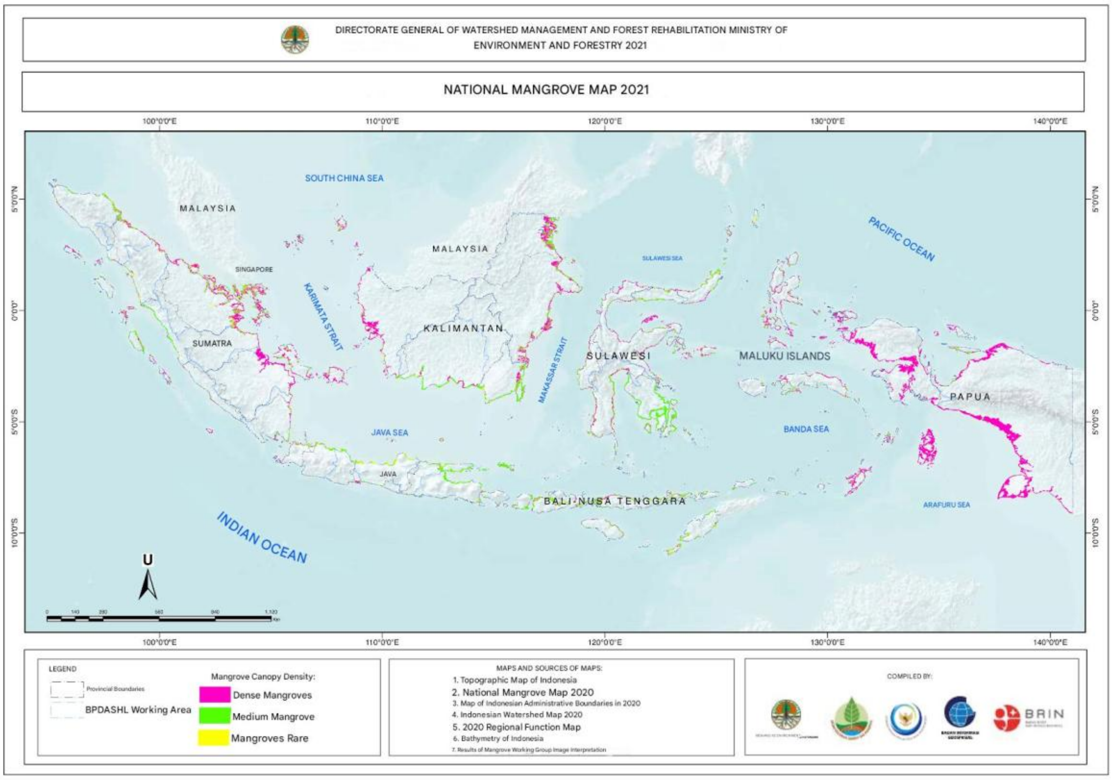

Figure 1. National mangrove map in 2021 (source: MoEF, 2021)

3.2 Current Annual Sequestration and Contribution to National Mitigation

Published sequestration rates applied to representative baseline areas suggest that Indonesia's coastal ecosystems collectively function as substantial natural carbon sinks, although the magnitude varies significantly by ecosystem type. Mangroves consistently dominate annual carbon uptake due to both their high per-hectare rates and their extensive national coverage, making them the primary contributor to Indonesia's coastal blue-carbon budget. In contrast, seagrass, salt marsh, and coastal peat ecosystems exhibit lower sequestration rates per unit area, yet still provide meaningful cumulative contributions when scaled across their respective distributions. Because this assessment relies entirely on secondary data, all estimates are expressed as ranges rather than precise national figures, reflecting the variability reported across studies and ecological conditions.

When aggregated, the synthesis produces an indicative national annual sequestration range, driven largely by mangroves and supplemented by other coastal ecosystems. Seagrasses add a notable secondary contribution, particularly due to their widespread presence, despite their modest per-hectare accumulation. Salt marshes—though limited in extent—still enhance total uptake, while coastal peatlands contribute more modest annual increments but store exceptionally large carbon stocks over long timescales. These combined contributions illustrate a diversified ecosystem-based mitigation portfolio, where each system, regardless of scale, plays a distinct and complementary role in strengthening Indonesia's nature-based mitigation capacity.

Although this study does not integrate official national emission inventories or precise NDC targets, an illustrative proportional comparison suggests that the aggregated coastal sequestration range could represent a small but meaningful share of Indonesia's wider mitigation landscape. When compared qualitatively to typical expectations for reductions in the land-use or forestry sector, the potential contribution of coastal ecosystems may reach a low single-digit percentage of a hypothetical sectoral target. While not a substitute for large-scale mitigation from high-emitting sectors, these ecosystems offer high-value, low-cost, and multi-benefit mitigation potential. Their contributions underscore the strategic importance of conserving, restoring, and expanding coastal ecosystems as part of Indonesia's integrated approach to achieving long-term climate commitments.

3.3 Degradation Drivers and Recent Trends

Numerous sources derived from national reports, case studies, and research articles, identify the main causes of blue carbon ecosystem decline in Indonesia. The aquaculture conversion, coastal infrastructure, land-based pollution, and sediment from upland erosion are strongly linked to this degradation (Figure 2). Since the 1980s, aquaculture conversion has led to extensive historical losses of mangrove ecosystems in some regions including Java, Sumatra, Sulawesi, and parts of Kalimantan. Coastal infrastructure and land reclamation have mainly affected small salt marsh areas in estuaries, resulting in habitat loss and hydrological disruptions. The seagrass habitat situated in areas like Bali, Lombok, and the Thousand Islands are being damaged by the artificial activities such as, land-based pollution, boat anchoring, and trampling linked to tourism. Although these drivers vary in importance by location, their cumulative and interacting effects consistently reduce ecological function and carbon retention capacity across all ecosystem types.

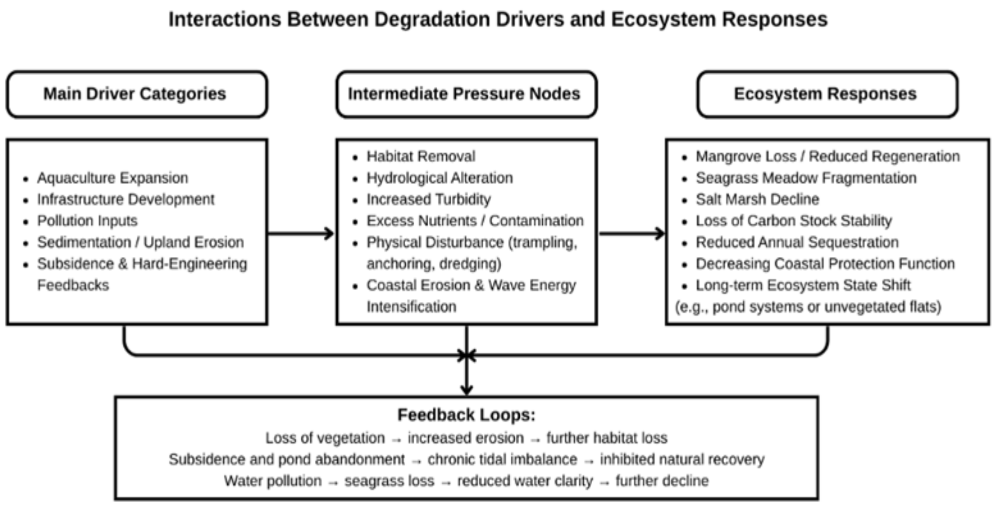

Figure 2. Interactions Between Degradation Drivers and Ecosystem Responses

The main direct cause of mangrove loss is the spread of aquaculture, especially shrimp ponds. At its worst, Indonesia lost 1–3% of its mangroves each year. Some areas in North Sumatra, South Sulawesi, and West Kalimantan lost even more. The establishment of ports, roads, and tourism sites adds pressure by altering water flow, fragmenting habitats, and accelerating erosion. Pollution from nutrients, wastewater, and plastic debris hits seagrass areas hardest. Studies show that losses of 2–5% annually in areas with heavy tourism. More sediment from upland erosion, often due to deforestation, buries seagrass beds and disrupts mangrove water flows. This worsens the impact of land conversion. These patterns show that, without better coastal planning and watershed management, long-term ecosystem decline is likely.

Case studies show how these factors damage ecosystems. In North Sumatra, converting mangroves into shrimp ponds destroys forests, alters water flow, and causes the ground to sink. This makes recovery difficult. In Bali's Sanur and Nusa Dua, ongoing tourism, boat anchoring, and untreated wastewater have thinned seagrass and broken it into patches. On Java's north coast, taking groundwater causes the land to sink. This increases shoreline erosion and leads to the construction of hard coastal barriers. These barriers worsen mangrove and nearshore vegetation loss. These examples show that human activities cause ecological harm through linked social, economic, and environmental factors. This highlights the need for restoration and management that address multiple causes and sectors.

Table 2. Major degradation drivers, geographic examples, and supporting evidence (secondary sources)

Degradation Driver	Typical Mechanism of Impact	Geographic Hotspots (Examples)	Reported Loss/Degradation Rates (Ranges)	Illustrative Case Evidence
Aquaculture conversion (especially shrimp ponds)	Direct clearing of mangroves, hydrological alteration, soil compaction and subsidence	North Sumatra, South Sulawesi, West Kalimantan, East Java	1–3% mangrove loss per year during peak expansion periods; higher (>3%) in localized districts	Rapid conversion to shrimp ponds leading to long-term loss of tidal flow and inhibited natural regeneration
Infrastructure expansion (ports, roads, reclamation)	Land reclamation, hydrological disruption, erosion acceleration, habitat fragmentation	Java north coast, Makassar coast, Balikpapan Bay	Localized mangrove/seagrass loss documented in project zones; variable rates (site-dependent)	Port expansion in Makassar associated with hydrological changes causing mangrove dieback
Pollution (nutrients, wastewater, plastics)	Light reduction, algal overgrowth, toxicity, smothering of benthic vegetation	Bali (Sanur, Nusa Dua), Lombok, Jakarta Bay	Seagrass degradation 2–5% annually in high-tourism zones	Tourism areas reporting meadow thinning due to trampling, anchoring, and wastewater

Sedimentation & upland erosion	Burial of seagrass, altered tidal channels, increased turbidity	North Java coast, South Sulawesi estuaries	Episodic die-off events; chronic decline in water clarity over time	Upland erosion increasing sediment load that buries seagrass beds in shallow inlets
Subsidence & hard-engineering feedbacks	Flooding of coastal vegetation, shoreline retreat, scouring around structures	North Java coastal corridor	No fixed rate; progressive mangrove and seagrass loss due to rising relative sea level	Subsidence-induced degradation triggering hard defenses, which then accelerate habitat loss

3.4 Scenario-Based Synthesis (Qualitative and Range Estimates)

The synthesis of secondary datasets and case-study evidence provides a comparative qualitative assessment of the three development trajectories, Business as Usual (BAU), restoration-driven, and engineering-integrated pathways. Under the BAU trajectory, most studies indicate a continuation of ecosystem decline driven by conversion, erosion, hydrological alteration, and limited enforcement, leading to progressive losses in ecosystem extent and condition. These losses translate into reduced annual sequestration capacity and erosion of long-term carbon stocks, as well as heightened vulnerability to coastal hazards. Qualitatively, BAU results in a downward trend across all indicators, with increasing uncertainty due to compounding climate and development pressures. The restoration-driven trajectory presents a more optimistic outlook, with empirical evidence showing that well-managed ecological rehabilitation efforts can recover biomass, soil carbon accrual, and ecological integrity over medium- to long-term timescales. However, recovery is typically slow, often requiring 5–20 years to realize significant carbon gains, and is vulnerable to setbacks such as re-conversion, weak governance, or hydrological misalignment. Despite these challenges, restoration alone generally delivers measurable improvements relative to BAU, especially in terms of natural recruitment, biodiversity enhancement, and partial recovery of sequestration functions.

Engineering-integrated trajectories demonstrate the strongest potential for accelerating positive outcomes by addressing underlying biophysical constraints that limit restoration success. Evidence from hybrid interventions—including permeable breakwaters, sediment-enhancement structures, eco-dykes, and hydrological rehabilitation—shows substantial improvements in substrate stability, sediment deposition, and seedling survival compared to ecological restoration alone. Although precise quantitative projections cannot be made without spatial modeling, qualitative multipliers derived from case studies suggest potential improvements such as 20–50% higher seedling survival, 30–70% reduced shoreline retreat, and significantly faster establishment of conditions conducive to long-term carbon accumulation. These engineering-supported pathways also appear to enhance ecosystem resilience, offer co-benefits for coastal protection, and reduce the risk of restoration failure. While uncertainties remain regarding scalability and long-term maintenance costs, the combined evidence indicates that engineering-integrated trajectories provide the most robust pathway for achieving durable carbon gains and climate-resilient coastal management in Indonesia.

Table 3. Comparative qualitative synthesis of expected outcomes under three trajectories

Outcome Dimension	Business as Usual (BAU)	Restoration-Driven	Engineering-Integrated
Ecosystem Extent Trend	Continued decline; localized losses in high-pressure zones	Slow to moderate recovery; dependent on site suitability	Moderate to accelerated recovery; improved stability in erosional zones
Annual Sequestration	Declining due to reduced ecosystem area and degradation	Gradual increase over decades; gains dependent on survival and recruitment	Higher and faster gains due to improved survival and sediment conditions
Long-Term Carbon Stocks	Net carbon loss; potential release from disturbed soils	Partial to substantial recovery over 10–30 years	Enhanced trajectory of soil carbon re-establishment due to stabilized hydrodynamics
Seedling/Vegetation Survival	Low survival in exposed or degraded settings	Moderate survival (typically 50–80%)	Higher survival (20–50% improvement compared to restoration-only cases)
Resilience to Erosion and Sea-Level Rise	Decreasing resilience; increased hazard exposure	Moderate improvement; natural processes partially restored	Significant improvement; engineering structures reduce wave energy and enhance accretion
Co-Benefits (biodiversity, livelihoods)	Declining	Moderate gains depending on restoration success	High gains due to stronger ecosystem stability and multifunctional benefits
Uncertainty Level	High (due to compounding pressures)	Moderate (depends on governance and ecological conditions)	Moderate to high (linked to engineering design, cost, and maintenance)
Overall Assessment	Negative trajectory	Positive but gradual improvement	Strongest pathway for measurable, durable gains

4. Discussion

4.1 Interpreting Ecosystem Evidence and Engineering Implications

The analysis demonstrates that Indonesia's blue carbon ecosystems, particularly mangroves and seagrass, hold substantial but uneven potential, which is strongly linked to management. Three distinct pathways show different trajectories, BAU leads to continuous carbon stock loss; restoration achieves moderate decadal recovery; and engineering-integrated approaches accelerate this recovery, reduce project failure, and create stable conditions essential for long-term carbon accumulation (Murdiyarso *et al.,* 2015). The full potential of Indonesia's blue carbon can be strategically influenced and achieved by aligning ecological restoration efforts with targeted engineering interventions (Schrag, 2007; Choudhary *et al.,* 2024).

Across the literature, engineering-integrated restoration consistently outperforms planting-only or ecological rehabilitation in settings characterized by erosion, hydrological disruption, or unstable sediment conditions. Hybrid measures (e.g., permeable breakwaters, eco-dykes, sediment nourishment structures) enable sediment trapping and hydrodynamic buffering, which in turn improve seedling survival rates by 20–50% and support faster rebuilding of substrate elevation capital. These mechanisms explain why engineering-nature approaches show greater robustness under high-energy coastal conditions and why restoration-only efforts often fail when placed in geomorphologically unsuitable areas (Choudhary *et al.,* 2024) Importantly, carbon-benefit trajectories also differ: above-ground biomass recovers within several years, soil carbon accrues more gradually, and full ecosystem functional maturity may take decades. This mismatch between ecological timelines and policy cycles, such as five-year NDC updates, implies that Indonesia must plan blue carbon strategies over medium-to-long horizons, while also integrating near-term actions that stabilize ecosystems and reduce carbon loss.

Ecosystem condition emerges as a critical mediator of carbon outcomes. Intact mangrove and seagrass systems show high natural sequestration and resilience, but degraded or fragmented systems often lose substrate stability, hydrology, and species diversity, undermining their capacity to recover without intervention. For heavily degraded hotspots, engineering support becomes not only beneficial but often necessary to re-establish preconditions for recovery. This reinforces that restoration approaches must be context-sensitive. Areas with good hydrological function may only require ecological planting, while erosion-prone shorelines demand hybrid designs. In short, Indonesia's blue carbon future is strongly conditioned by the interplay of ecological baselines, hydrodynamic processes, and engineering support systems (Ramadhan *et al.,* 2024; Wang *et al.,* 2025).

4.2 Policy, Planning, Socio-economic Co-benefits, and Climate Communication

The empirical patterns offer several implications for national climate policy, development planning, and coastal management. First, recognizing that Indonesia's blue carbon mitigation potential is subject to variation and uncertainty, it is nonetheless crucial to meaningfully include this capacity in national climate commitments, particularly targeting the NDC's coastal and FOLU (Forestry and Other Land Use) sectors (Krott, 2005; Alongi *et al.,* 2015). Although this study uses qualitative estimates rather than modeled outputs, the ranges identified here can help frame blue carbon as a complementary mitigation pathway. Policymakers could introduce indicative sub-targets for coastal ecosystems, integrate blue carbon baselines into climate inventories, and adopt hybrid engineering–nature measures as part of national adaptation and resilience strategies (Abidin *et al.,* 2021; Hanson, 2025).

The findings highlight the critical need to harmonize and update coastal infrastructure planning nationally and regionally. Engineering designs must incorporate nature-based and hybrid solutions, requiring coastal protection standards to include ecological co-benefits and carbon considerations (Choudhary *et al.,* 2024). Furthermore, all financing, including public funds and carbon markets must prioritize interventions that demonstrate strong evidence of carbon recovery and resilience. To secure investment, especially for market-linked projects, effective MRV

(Monitoring, Reporting, and Verification) systems are essential, which must track both ecological and engineering metrics (Murdiyarso *et al.,* 2022).

Third, socio-economic and biodiversity co-benefits must be recognized as integral to Indonesia's blue carbon strategies. Restoration and engineering-nature interventions can strengthen fisheries production, improve habitat quality, stabilize coastlines, and support livelihoods through ecotourism, sustainable fisheries, or community-based conservation enterprises (Kustanti *et al.,* 2012). Case studies show that hybrid solutions often improve fish nursery habitats, re-open natural waterways, and reduce storm impacts, providing direct benefits to coastal communities. However, there are trade-offs: engineered structures may restrict access, alter traditional resource use, or concentrate benefits unevenly. Participatory planning and community co-management are essential to ensure equitable outcomes and foster the sustainable success of these interventions (Vanderklift *et al.,* 2019; Vinata *et al.,* 2024).

Finally, environmental communication is critical to foster understanding of environmental issues (Ardian, 2019). Beyond merely disseminating information, its primary goal is to achieve a shared vision of a sustainable future and build the capacity within social groups to resolve or prevent problems (Effendy, 2008). Nonetheless, environmental communication essentially serves two primary functions, pragmatic function which encompasses the roles of education, warning, mobilization, and persuasion; and constitutive function, wherein language and other symbols play a critical role in shaping our perception of the reality and nature of environmental problems (Cox R, 2013). Crucially, it bridges environmental issues with sociopolitical processes, using educational activities to translate knowledge into behavioral change and action. This necessity for clear communication extends specifically to climate-related efforts, where effective climate communication strategies are essential to ensure that all stakeholders including communities, policymakers, and the general public understand the value of specific assets, such as blue carbon ecosystems. This comprehension is vital for enhancing the credibility, and long-term sustainability of these environmental programs (Ardian, 2019; Cangara, 2022).

4.3 Constraints, Prioritization, Implementation Pathways, and Research Needs

Despite the promising potential identified, several constraints and risks must be acknowledged. Carbon estimates derived from secondary data remain subject to uncertainty due to differences in measurement protocols, ecological variability, and limited national-scale baselines for seagrass and saltmarsh ecosystems. Restoration carries well-known risks of failure (Bell, 2016), especially in areas facing continuous erosion, land subsidence, or inadequate hydrological conditions. Governance barriers, including unclear land tenure, weak enforcement, incentive misalignment, and limited cross-sector coordination pose additional challenges. Environmental uncertainties, such as sediment supply reduction, upstream land-use impacts, and accelerated sea-level rise, may limit long-term ecosystem viability or lead to maladaptation if hybrid structures are poorly designed.

Given the technical and ecological complexity of engineering-integrated interventions, careful site prioritization and risk management are essential. While such approaches can stabilize hydrodynamics and improve restoration success in erosion-prone or heavily degraded areas, evidence also shows that poorly designed structures may fail due to inadequate sediment supply, improper hydrological alignment, extreme wave conditions, or insufficient maintenance, potentially leading to maladaptation or additional habitat loss. Therefore, engineering-integrated solutions should be applied selectively, based on local sediment dynamics, ecosystem condition, governance capacity, and socio-economic dependence, and implemented through phased pilots rather than direct large-scale deployment. Continuous monitoring of both ecological indicators (e.g., survival rates, sediment accretion, canopy recovery) and structural performance is necessary to detect early failures and adjust designs before scaling up interventions.

The study highlights several critical research needs. Indonesia requires more field-based carbon baselines, especially for below-ground and soil carbon compartments across sediment types and hydrological regimes. Longitudinal monitoring of hybrid engineering–nature interventions is essential to quantify carbon recovery trajectories and resilience outcomes over time (Choudhary *et al.,* 2024). There is also a pressing need for life-cycle analysis and cost–benefit assessments comparing restoration-only, engineering-only, and hybrid approaches to inform national budgeting and investment strategies, as the high capital costs, long-term maintenance requirements, and potential for unintended environmental or social externalities associated with large-scale coastal interventions necessitate robust financial justification and optimization of public spending (Barbera *et al.,* 2022; Hanson *et al.,* 2025).

Finally, Indonesia should strengthen blue-carbon MRV systems, combining ecological survey methods, engineering monitoring protocols, remote sensing, and community-based monitoring to support climate finance, policy integration, and transparent reporting (Murdiyarso *et al.,* 2022; Meng *et al.,* 2023).

5. Conclusion

This review addresses how Indonesia's blue carbon ecosystems can be sustained and enhanced under different development pathways. The synthesis confirms that Indonesia holds globally significant blue carbon stocks, yet their extent, condition, and sequestration capacity are highly heterogeneous and increasingly constrained under a Business-as-Usual trajectory marked by continued degradation. Evidence from restoration case studies demonstrates that carbon recovery and ecosystem functionality can be re-established over multi-year timeframes, although outcomes remain strongly site-specific and dependent on hydrological conditions, species selection, governance, and post-restoration management. Crucially, the review finds consistent evidence that engineering-integrated approaches, such as permeable breakwaters, sediment enhancement, and eco-dykes, can materially improve restoration stability, survival rates, and long-term resilience compared with ecological restoration alone, particularly in erosion-prone and highly altered coastal settings. In response to these findings, the study underscores the need to embed blue carbon considerations into national climate strategies and coastal infrastructure planning, prioritize hybrid engineered–nature solutions where ecological constraints are high, strengthen community participation and tenure security, and establish technical standards and monitoring frameworks for implementation. Although limited by its reliance on secondary data and the absence of spatial modeling, this review provides a coherent, evidence-based framework that clarifies how engineered–nature interventions can be strategically applied to enhance Indonesia's coastal carbon outcomes and climate resilience.

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