RECLAIMING THE SHORELINE WITH MODULAR BIOCARBON: SEAWEED AND FLY ASH BEYOND CARBON COLONIALISM

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Abstract. *"Why do vulnerable communities bear climate debt, while major emitters remain insufficiently regulated and accountable?" Coastal ecosystems are among the Earth's most vital yet vulnerable frontlines, threatened by erosion, seawater intrusion, sea level rise, and the compounding effects of climate change. These risks not only endanger marine biodiversity but also fracture the socio-economic lifelines of communities that did the least to cause the crisis. This innovation introduces Modular Biocarbon Technology, a nature-based, community-driven solution constructed from seaweed, a fast-growing carbon-absorbing biomass, and fly ash, an industrial byproduct rich in pozzolanic compounds. These two materials are fused into adaptive, site-specific modules that reduce wave energy, capture sediment, support recovery of marine biodiversity, and, most critically, serve as permanent carbon sinks through biochar stabilization. In the era of global climate injustice, where nations like Indonesia are expected to act as planetary lungs without equitable compensation. This solution reframes our ecological burden as a modular climate asset. It offers leverage in the discourse on carbon debt, asserting that frontline communities deserve agency, not austerity. Aligned with SDGs 11, 13, and 14, this solution is scalable, replicable, and deeply rooted in local participation. It empowers coastal actors to reclaim degraded shorelines, while catalyzing a circular economy that transforms industrial waste into tools of resistance and regeneration. By bridging environmental science, material innovation, and social equity, this initiative provides a bold, implementable blueprint for coastal resilience, carbon justice, and national decarbonization.*
Keywords: *carbon sequestration, carbon debt, circular economy, coastal resilience, modular biocarbon technology*

INTRODUCTION

Oceans, our planet's lungs and climate stabilizers, have transformed into silent battlegrounds of climate injustice. Coastal and maritime communities, particularly across the Global South, contribute least to global emissions yet suffer most from rising sea-levels, seawater intrusion, and biodiversity collapse (Harris, 2012; Martinez-Alier et al., 2014). This asymmetry is not a coincidence, it is a consequence of prolonged extractivism and systemic neglect by high-emission powers. Global climate responsibility frameworks also emphasize fairness in emissions and obligations between nations (Pogge et al., 2015).

In Indonesia, this injustice is lived. With over 80,000 kilometers of coastline and thousands of small islands, Indonesia stands on the frontlines of the climate crisis (Ministry of Environment and Forestry, 2022). Yet, its coastal resilience remains overshadowed by land-centric policies and infrastructural paradigms that reinforce centralization and carbon dependency (Climate Governance Initiative Indonesia, 2023). The nation's Net-Zero commitment by 2060 risks becoming a performative gesture if frontline realities like coral bleaching, coastal erosion, and small island displacement remain excluded from both budget and blueprint.

This research responds not with passive observation, but with restorative resistance. We propose seaweed-based bio-concrete enhanced with fly ash not only as a scientific breakthrough, but as a symbolic shift, from land-bound, high-carbon development toward decentralized, regenerative, ocean-rooted futures. Seaweed, a native marine biomass, embodies both ecological intelligence and post-extractive potential, while fly ash, an industrial byproduct, allows us to reclaim and repurpose waste from the very systems we seek to transform (Christiawan, 2021). Together, they offer an alternative to the concrete hegemony that dominates climate adaptation today. As marine biologist Sylvia Earle (2009) reminds us, "No blue, no green. If the ocean dies, we die." In honoring that truth, this study stands not just as a design but as a call to reimagine climate resilience through decolonial, community-powered innovation.

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METHODOLOGY

This study adopts a theoretical and literature-based approach, drawing from scientific publications, environmental reports, and previous research to explore alternative possibilities within the field of engineering. Materials such as seaweed-based biopolymers and fly ash are not tested experimentally; instead, they are analyzed through existing studies with emphasis on their potential for technical application and ecological impact.

The approach is exploratory in nature, aiming to synthesize existing knowledge, connect different research contexts, and identify opportunities for innovation in sustainable construction materials. Rather than providing experimental validation, this study seeks to highlight emerging material strategies and their relevance to current environmental challenges.

The growing demand for sustainable construction has led to increased interest in alternative materials that reduce environmental impact while maintaining performance. Materials such as fly ash and seaweed-derived biopolymers, once considered peripheral, are now gaining attention as part of low-carbon and circular construction approaches (Christiawan, 2021; Martinez-Alier et al., 2014).

Repositioning Fly Ash: From Industrial Residue to Functional Binder

Fly ash, a fine particulate byproduct of coal combustion, has long demonstrated pozzolanic activity that enhances concrete performance by improving compressive strength, reducing permeability, and moderating thermal reactivity (Christiawan, 2021). Recent studies have shown that partial replacement of Portland cement (≈20%) with fly ash can significantly improve mechanical resilience and durability under saline exposure, supporting its application in marine-bound construction.

Seaweed Biopolymers: The Underutilized Marine Resource

In parallel, brown macroalgae such as *Laminaria* and *Sargassum* offer a renewable source of biopolymers, particularly alginate, known for their biodegradability, hydrophilic nature, and ability to function as natural binders or admixtures. Several studies and regional initiatives in countries such as Korea and Japan have explored marine biomass valorization, integrating seaweed derivatives into bio-concrete, self-healing mortars, and lightweight composites. However, globally, this resource remains underutilized in large-scale construction applications.

Toward a Convergent Innovation

The conceptual breakthrough lies in hybridizing fly ash with seaweed-based biopolymers, combining industrial waste with marine bioresources to engineer materials that are both low-carbon and high-performance. Existing literature, however, tends to treat these materials separately, fly ash in cementitious systems and seaweed in niche bio-based materials leaving their combined potential relatively unexplored.

Research Gap and Rationale

This study seeks to address this gap by examining the integration of fly ash and seaweed biopolymers within a modular coastal protection framework. This approach not only offers a material-based solution but also aligns with broader efforts to reduce carbon intensity in infrastructure systems and promote circular resource utilization (Martinez-Alier et al., 2014; Oulu, 2016). In doing so, this work positions underutilized materials as potential contributors to the development of sustainable and low-carbon built environments.

RESULTS AND DISCUSSION

To provide clarity and depth, this section is divided into two main parts: the Results, which articulate the ideation process and analytical findings derived from a synthesis of engineering precedents, design principles, and critical literature; and the Discussion, which serves to interrogate and contextualize these insights within the broader framework of national low-carbon strategies, infrastructural diplomacy, and the evolving

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discourse on carbon debt as both a technical liability and a geopolitical currency.This layered structure allows the findings to be not only technically grounded but also politically consequential bridging empirical outcomes with the state's ambition to reconcile industrial development, energy transition, and climate accountability in one infrastructural gesture.

Results: Synthesizing Infrastructure, Carbon Logic, and Territorial Futures

The design exploration presents an infrastructure that transcends the conventional role of utility, instead reframing it as a territorial negotiator and a symbol of Indonesia's climate-era diplomacy. This design is anchored on three critical layers, namely typological-morphological precedent, carbon-integrated calculations, and territorial programming.

The typological-morphological approach draws from hybrid infrastructure models such as the "energy-landscape" interface observed in Scandinavian countries and coastal mitigation structures in the Netherlands. It integrates multiple functions, including seawater barriers, energy capture, and land reclamation, while enhancing spatial resilience and socio-environmental performance. This is reflected in the proposed elevated tidal defense spine incorporating solar-saline panels and adaptive platforms designed to accommodate sediment migration and future urban demands.

In terms of carbon-integrated calculations, the system combines projected emission avoidance through fossil fuel substitution with carbon absorption mechanisms via constructed wetlands and solar-saline arrays. This enables a net-zero-plus strategy that not only offsets but exceeds the embodied carbon generated during construction. The projections are informed by lifecycle analysis (LCA) benchmarks derived from the Global Carbon Project and Indonesia's National Energy Outlook (RUEN 2021).

Furthermore, the territorial programming extends beyond physical infrastructure by creating a multifunctional landscape that integrates environmental restoration and socio-economic activities. The design incorporates carbon monitoring stations, desalination nodes, aquaculture experimentation zones, and educational spaces related to energy transition, transforming the project into a comprehensive ecosystem rather than a singular infrastructural object.

Discussion: Beyond Metrics, Carbon Debt as Infrastructure Diplomacy

Infrastructure has traditionally been evaluated in terms of cost, performance, and durability. However, this study repositions carbon as a geopolitical metric, particularly in the Indonesian context where energy demand continues to rise and coal remains a dominant energy source. Within this framework, carbon is no longer solely an environmental liability but also a strategic instrument. The proposed design responds to the national carbon market roadmap (IDXCarbon), emphasizing the need for state-owned enterprises and strategic regions to quantify, trade, and balance emissions.

The proposal also aligns with Indonesia's broader energy transition narrative, including Pertamina's Net Zero Emission 2060 roadmap. By integrating decentralized renewable technologies and community-scale benefits, such as water access, microgrids, and aquaculture platforms, the design supports frameworks like the Just Energy Transition Partnership (JETP), ensuring that decarbonization is participatory rather than imposed.

At the same time, the project challenges long-standing patterns of extractive urbanism along Indonesia's coastline. Instead of reinforcing environmentally damaging development, it introduces an alternative approach that combines ecological restoration with productive infrastructure, shifting from a "build-to-consume" paradigm toward "build-to-recover."

Finally, the concept of diplomatic territorialism positions coastal infrastructure as part of Indonesia's broader climate strategy. In a regional context where countries compete for climate financing and green investment, this approach frames Indonesia as a proactive actor capable of initiating environmental innovation and contributing meaningfully to global climate discourse.

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Synthesis: Rewriting the Infrastructure Playbook

What emerges from the analysis is a provocation: that infrastructure can be more than technical, it can be visionary. It can be part of a new statecraft, one where design negotiates not only with land and water, but with future debts, transitional narratives, and geopolitical legitimacy.

Indonesia does not lack ambition, it needs infrastructure that matches the scale and depth of its geopolitical moment. This project is a prototype of that ambition: a spatial, technical, and symbolic assertion that the country is ready not only to mitigate its past, but to design its future, with intelligence, courage, and strategy.

CONCLUSIONS AND SUGGESTION

This research emerges from a generational unrest, an anxiety not just rooted in climate data, but in the lived reality of how infrastructure continues to mirror global injustice and perpetuate carbon inequality. Through a close reading of literature and design precedents, this paper argues that carbon debt is not just an ecological metric, it is a geopolitical weight. It dictates who gets to emit, who gets to build, and who is left to bear the burden.

We find that infrastructure is never neutral. It is scripted by systems of extraction, colonial legacy, and deferred responsibility. In an era of escalating climate crisis, the blueprint must shift, from efficiency to accountability, from growth to justice. Carbon equity is no longer an ideal; it is a design imperative.

The path forward demands more than reducing footprints, it requires reckoning with the carbon debts embedded in infrastructures of the Global South. This debt is not a relic of the past; it is reproduced in the present and disproportionately paid by nations like Indonesia. For a generation inheriting this imbalance, silence is complicity. Infrastructure must be reclaimed as a frontline of climate justice.

Practical Suggestions

Practical implementation of the proposed approach requires stronger integration between infrastructure master planning and decarbonization strategies. In addition, regulatory frameworks and fiscal incentives should be introduced to encourage carbon-equitable design and life-cycle-based planning. Strengthening international climate diplomacy is also essential to ensure that infrastructure development in the Global South does not replicate carbon-intensive pathways established by the Global North.

Suggestions for future research

Future research is needed to further develop the concept of carbon debt within infrastructure systems. While this study discusses carbon debt in broad spatial and political terms, subsequent studies could focus on quantifying carbon inheritance at the scale of individual infrastructures or sectors, such as transportation, energy, and water systems, particularly in postcolonial regions.

Additionally, further research is encouraged to explore alternative design paradigms that incorporate not only environmental efficiency but also historical responsibility, ensuring that infrastructure serves as a tool for climate justice rather than solely climate mitigation. Longitudinal case studies examining intergenerational decision-making and infrastructure adaptation over time may provide deeper insights into how climate-conscious design practices evolve across different socio-economic contexts.

Finally, as carbon metrics become increasingly politicized, future studies could investigate how the concept of carbon equity is negotiated within global policy forums and how these negotiations influence local infrastructure planning in vulnerable nations.

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