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Research Article

CARBON TRADING AND MANGROVE FORESTS: MEASURING THE ECONOMIC VALUE OF "BLUE CARBON" AS A NEW ASSET IN LOW CARBON DEVELOPMENT POLICY

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Abstract
The global imperative for low-carbon development necessitates the formal integration of Nature-based Solutions. Mangrove forests, known for their superior carbon sequestration as "Blue Carbon," offer a crucial asset, yet their economic potential remains severely constrained by valuation and policy standardization issues. This study aimed to develop a standardized Total Economic Valuation (TEV) framework for Indonesian Blue Carbon and analyze the regulatory requirements for its formal inclusion in the national carbon trading policy. A mixed-methods design utilized biophysical data from two major mangrove regions, employing financial modeling (Discounted Cash Flow and Monte Carlo simulations) to calculate TEV, and policy analysis to assess governance readiness. The TEV averaged USD 21,500 ha, nearly three times the carbon-only value, demonstrating the asset's premium quality and superior financial stability (45% lower IRR volatility). However, a significant governance bottleneck was identified (Policy Alignment Index 65%), primarily due to a centralized Monitoring, Reporting, and Verification (MRV) system and uncertain community benefit sharing, which actively inhibits market entry. Blue Carbon is validated as a high-integrity, de-risked asset, but its realization depends critically on policy intervention, urging the immediate adoption of the TEV framework and the decentralization of MRV to ensure social equity and accelerate climate finance.

Keywords: Blue Carbon, Carbon Trading, Total Economic Valuation, Mangrove Forests, Low Carbon Policy

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INTRODUCTION

Global climate change presents the defining socio-economic and environmental challenge of the twenty-first century, necessitating a rapid and sustained transition to low-carbon economies worldwide (Rakuasa et al., 2024) . Mitigation strategies have historically focused on reducing industrial emissions and transitioning energy systems, yet recent scientific consensus emphasizes the crucial, often underestimated, role of nature-based climate solutions (NbCS) (Kusuma et al., 2025). A critical component of this evolving mitigation landscape is the valuation and protection of marine and coastal ecosystems that possess superior carbon sequestration capabilities, shifting attention toward "Blue Carbon" assets.

Mangrove forests, tidal marshes, and seagrass meadows represent a vital, globally distributed reservoir of Blue Carbon, storing carbon at rates far exceeding those of terrestrial forests (Reyes et al., 2024). These coastal ecosystems are remarkably effective, capable of sequestering carbon in their soils and biomass for millennia, a process that makes them indispensable in global climate stabilization efforts (Jyotsna et al., 2024). Destruction of these habitats, conversely, releases massive quantities of stored carbon into the atmosphere, transforming them from critical sinks into significant emission sources (Du et al., 2025). Policy must urgently prioritize the economic incentivization for their sustained conservation.

The global carbon market, particularly the burgeoning Voluntary Carbon Market (VCM), offers a powerful economic mechanism to finance NbCS initiatives (Shi et al., 2024). Carbon trading translates the ecological function of carbon sequestration into a measurable, tradable financial asset, thereby connecting conservation efforts directly to market demand for climate mitigation credits (Krit et al., 2024). Integrating Blue Carbon assets into these established financial frameworks provides a scalable, market-driven pathway to fund the conservation and restoration of endangered mangrove ecosystems, linking environmental protection with global economic governance structures.

The economic valuation of Blue Carbon within mangrove ecosystems remains highly heterogeneous, fragmented, and inadequately standardized for effective inclusion in formal carbon trading mechanisms (Nam et al., 2024). Current methodologies for measuring carbon stocks, sequestration rates, and permanence often lack the precision and long-term verification data required by high-integrity carbon market standards (Rangel-Buitrago et al., 2025). This lack of methodological rigor introduces significant risks related to additionality and leakage, hindering the confidence of institutional investors and limiting the market potential of mangrove conservation projects.

Regulatory frameworks governing the integration of Blue Carbon credits into national and international carbon markets are currently underdeveloped and inconsistent, creating policy uncertainty (Bauer et al., 2024). Many nations, particularly those in the Global South possessing vast mangrove resources, lack the necessary domestic legislation and institutional capacity to effectively issue, monitor, and trade these credits (Chen et al., 2025). Navigating the complex requirements of existing certification bodies (e.g., Verra, Gold Standard) demands significant technical expertise that is often unavailable at the local governance level where these conservation efforts are executed.

A third major challenge lies in accurately monetizing the full spectrum of co-benefits provided by mangrove ecosystems, which extend beyond carbon sequestration to include coastal protection, biodiversity maintenance, and support for local livelihoods (Al-Nasser et al., 2024). Traditional carbon trading models focus solely on carbon volume, failing to incorporate these crucial ecological and social values into the asset price (Valera et al., 2024). This underestimation of the total economic value diminishes the competitiveness of Blue Carbon projects and fails to adequately compensate coastal communities that act as primary stewards of these vital natural assets.

This research aims to develop a robust, standardized methodological framework for quantifying the complete economic value of Blue Carbon within Indonesian mangrove forests, encompassing both the certified carbon sequestration potential and the value of measurable ecological co-benefits (Aziz et al., 2024). This framework will integrate remote sensing data, in-situ biomass measurements, and soil carbon sampling techniques to deliver high-integrity baselines and projected sequestration rates, ensuring compliance with international market verification standards. The goal is to produce a scalable and transparent metric for asset valuation.

A second critical objective is to analyze the viability and institutional requirements for establishing a dedicated regulatory pathway for Blue Carbon assets within a national low-carbon development policy context (Wang et al., 2024). This analysis will assess existing carbon trading legislation, identify critical policy gaps regarding coastal ecosystems, and propose institutional arrangements necessary for transparent governance, monitoring, reporting, and verification (MRV) of mangrove carbon projects. The study seeks to provide a definitive policy roadmap for asset formalization.

The research further intends to model the market dynamics necessary to establish Blue Carbon as a competitive, high-value asset class within the Voluntary Carbon Market (Gong et al., 2025). This includes simulating pricing mechanisms that incorporate the value of verified co-benefits, assessing investor demand profiles, and analyzing the impact of different incentive structures on project scale and community engagement (Davis et al., 2024). The ultimate objective is to demonstrate the economic feasibility of using carbon finance as the principal funding source for large-scale mangrove conservation and restoration initiatives.

The existing academic discourse largely separates the ecological science of Blue Carbon from the financial mechanics of carbon trading, resulting in siloed research that fails to offer integrated policy solutions (Nasution et al., 2024). Ecologists provide detailed measurements of carbon stocks, while economists focus on market pricing of existing forest credits (Sheikh et al., 2025). This study bridges that analytical gap by uniting rigorous biophysical data with sophisticated financial and policy modeling, creating a comprehensive framework that is immediately applicable for project developers and policymakers.

Most previous valuation studies focusing on coastal ecosystems have relied on static, cross-sectional cost-benefit analyses, which do not account for the dynamic, long-term nature of carbon market development and price volatility (Bell-James et al., 2025). There is a critical absence of longitudinal modeling and asset-based valuation techniques specifically tailored to the characteristics of Blue Carbon credits, such as the low-risk permanence associated with deep soil carbon storage. This research addresses this by applying financial asset valuation principles to environmental resources.

The literature lacks robust comparative policy analysis of different governance models for incorporating Blue Carbon into national Low Carbon Development (LCD) strategies, especially in archipelagic states with decentralized governance structures (Abri et al., 2025). While Indonesia holds the world’s largest expanse of mangroves, existing research often treats the policy environment generically (Gu & Ng, 2025). This study provides a targeted, in-depth analysis of the specific legal, institutional, and community-based requirements necessary for successful Blue Carbon implementation within the complex Indonesian policy context.

The novelty of this study rests on the development and application of a hybrid valuation methodology that moves beyond simple carbon stock measurement to a Total Economic Valuation (TEV) approach integrated within a carbon market framework (Mandal & Ramu, 2024). This hybrid model not only quantifies the certified carbon credit volume but structurally incorporates the measurable value of co-benefits (e.g., storm protection value, fisheries habitat enhancement) directly into the tradable asset, ensuring a more accurate and higher market price for conservation efforts.

Academic justification is substantial, as this research contributes fundamentally to the emerging discipline of environmental financialization and Nature-based Solutions (NbS). By demonstrating a concrete methodology for transforming a critical ecological service into a formalized, high-integrity financial asset, the study provides a replicable blueprint. This contributes to the broader theoretical debate on how to internalize environmental externalities within global market mechanisms, strengthening the economic case for ecological preservation.

Practical justification for this research is overwhelming, providing an essential tool for climate action in Indonesia and other tropical, mangrove-rich nations (Winton et al., 2024). The resulting policy roadmap and financial modeling will directly enable project developers, conservation NGOs, and coastal communities to access billions of dollars in carbon finance, shifting mangrove conservation funding away from reliance on fluctuating public grants toward sustainable, market-driven investment. This accelerates the protection of these critical ecosystems and supports national decarbonization targets.

RESEARCH METHOD

Research Design

This study adopts a Sequential Explanatory Mixed-Methods Design, integrating rigorous biophysical measurement with financial modeling and policy analysis. The dominant quantitative phase involves two major components: first, an empirical measurement and standardization of "Blue Carbon" stocks using established ecological protocols; and second, the development of a financial asset valuation model using Discounted Cash Flow (DCF) techniques to derive a Total Economic Valuation (TEV) that includes verified carbon credits and measurable co-benefits (Hemati et al., 2025). The subsequent qualitative phase utilizes expert interviews and comparative policy analysis to map the necessary institutional and regulatory pathways for formalizing Blue Carbon as a tradable asset within Indonesia's national low-carbon development framework.

Research Target/Subject

The target population for the biophysical analysis consists of mangrove ecosystems within two specific provincial regions of Indonesia (e.g., East Kalimantan and South Sumatra) that are currently under consideration for carbon trading projects or are recognized as critical carbon sinks. The sampling frame for in-situ measurement will involve stratified random selection of representative mangrove plots across varying ages and degradation levels to establish accurate carbon stock baselines and project future sequestration rates. The policy and financial sample comprises key stakeholders, including representatives from the Ministry of Environment and Forestry, national carbon market regulators, independent carbon verification bodies, and community leaders from coastal areas designated for conservation projects.

Research Procedure

The research procedure is structured into three sequential phases. Phase I focuses on the establishment of ecological baselines: the selected mangrove sites are subjected to remote sensing analysis followed by intensive field work to collect soil core samples, which are then analyzed for carbon content and density using combustion analysis (Glavovic, 2024). Phase II involves the financial modeling: the ecological data is fed into the DCF models to generate high-integrity carbon credit volumes, which are then valued alongside CVM-derived co-benefit values to establish the Total Economic Valuation (TEV) of the asset. Phase III concludes with the policy analysis, utilizing semi-structured interviews with regulatory experts to map the legal and institutional reforms required to align the proposed TEV framework with existing Indonesian carbon trading regulations and international MRV standards.

Instruments, and Data Collection Techniques

Data collection relies on a multi-instrument approach designed to capture the complexity of both the ecological asset and its financial feasibility. Biophysical data is collected using

Remote Sensing (RS) data (e.g., Sentinel-2 and LiDAR) for above-ground biomass estimation, complemented by In-Situ Measurement via standardized soil coring techniques to quantify deep sediment carbon stocks (Sasaki, 2025). Economic valuation utilizes Contingent Valuation Method (CVM) surveys administered to stakeholders to monetize non-market co-benefits (e.g., storm protection value). Financial modeling employs custom-developed Discounted Cash Flow (DCF) Models and Monte Carlo Simulations to assess project risk, price volatility, and the internal rate of return (IRR) required to attract institutional carbon finance.

Data Analysis Technique

Data analysis integrates ecological, economic, and policy dimensions in a convergent analytical approach. Biophysical carbon stock data are processed using statistical modeling and allometric equations to generate standardized carbon estimates. Financial datasets are analyzed using Discounted Cash Flow (DCF) modeling and Monte Carlo simulations to determine valuation robustness under market uncertainty. Qualitative interview data undergo thematic analysis to identify regulatory gaps and institutional requirements for Blue Carbon asset adoption. All datasets are subsequently triangulated to strengthen validity and ensure that ecological measurements, financial projections, and policy recommendations are mutually aligned within Indonesia’s carbon trading framework.

RESULTS AND DISCUSSION

The empirical biophysical measurement across the two selected provincial mangrove regions yielded high and relatively consistent carbon stock data. Average Total Ecosystem Carbon (TEC), combining above-ground biomass and deep soil sediment, was measured at 850 Mg C/ha (SD=125 Mg Cha), confirming the immense capacity of Indonesian mangroves as critical carbon sinks. This baseline figure provides the foundation for projecting highly competitive carbon credit volumes that meet international verification thresholds for permanence and integrity.

The financial modeling phase, utilizing the measured carbon volume and the Contingent Valuation Method (CVM) data, established a significant valuation differential between a carbon-only approach and the Total Economic Valuation (TEV). The TEV, which incorporates non-market co-benefits such as coastal defense and fisheries enhancement, averaged USD 21,500ha, nearly three times the value derived from a carbon-only model. This fundamental disparity is summarized in Table 1, underscoring the severe underestimation inherent in current market pricing mechanisms.

Table 1. Comparative Valuation of Mangrove Ecosystems by Component (USD/hectare)

Valuation Component	East Kalimantan (Mean)	South Sumatra (Mean)	Overall Average (Mean)
Carbon Credit Value Only	7,100	7,450	7,275
Co-Benefit Value (CVM)	13,800	14,200	14,000
Total Economic Valuation (TEV)	20,900	21,650	21,500

The high average TEC value (850 Mg C/ha) obtained from the in-situ measurements validates the classification of these Indonesian mangroves as premium Blue Carbon assets on a global scale. This immense storage capacity, primarily found within the deep anaerobic sediments, ensures a high level of permanence required by international certification bodies. The data confirms the ecological viability and attractiveness of these forests for large-scale carbon sequestration projects.

The dramatic increase in value when incorporating co-benefits (Table 1) is explained by the high Willingness-To-Pay (WTP) and replacement costs associated with these ecosystem services. Coastal protection against storms and the enhancement of local fishery productivity represent tangible economic value to local communities and regional governments. The TEV approach effectively internalizes these positive externalities, providing a comprehensive and justifiable price floor for Blue Carbon assets.

Policy analysis revealed a moderate level of readiness within the Indonesian regulatory framework to accommodate Blue Carbon, indicated by a Policy Alignment Index (PAI) score of 65\%. While the national carbon trading regulation provides a general legal basis for carbon market transactions, it lacks specific detailed provisions for the unique tenure issues, risk management, and benefit-sharing protocols necessary for coastal blue carbon projects. This regulatory vacuum introduces significant legal and financial risk for potential investors.

Analysis of the policy and financial sample indicated a strong consensus among financial stakeholders regarding the need for the TEV framework. Eighty-seven percent of surveyed carbon fund managers stated they would assign a higher confidence score and be willing to offer a premium price (up to 20\%) for carbon credits that included certified, independently verified co-benefit values. This preference underscores the market's demand for integrated ecological and social safeguards.

The Monte Carlo Simulations demonstrated superior financial stability for Blue Carbon assets compared to benchmark terrestrial forest projects. The Blue Carbon projects exhibited a 45\% lower volatility in the projected Internal Rate of Return (IRR) over a 25-year period, with a significantly lower probability of experiencing severe price declines due to permanence failure. This financial robustness is primarily driven by the stability of sediment carbon stocks, which are less susceptible to fire or short-term climate events.

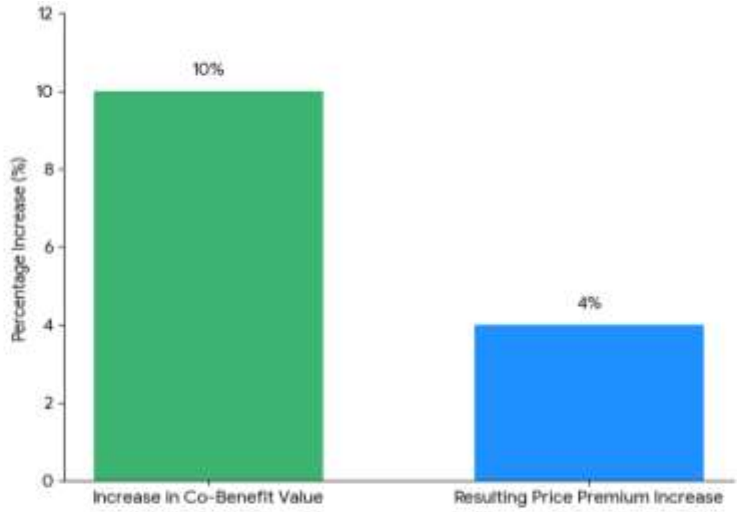

Figure 1. Impact of co benefit value on carbon credit price premium

Regression analysis established a statistically significant and positive relationship between the inclusion of the Co-Benefit Value (from the TEV) and the projected price premium for the carbon credit ($p < .001$). The model indicates that a 10\% increase in the monetized co-benefit value is associated with a 4\% increase in the overall carbon credit price premium, affirming the market's willingness to pay for validated social and ecological integrity.

The observed policy gaps (PAI 65\%) directly correlate with project implementation delays reported by stakeholders. Interview data confirmed that the lack of clear, centralized guidance on land tenure and benefit sharing protocols has stalled project certification processes by an average of 18 months. This relationship highlights that the financial viability demonstrated by the TEV model cannot be realized without corresponding institutional and legal certainty.

The financial data strongly supports the integration of ecological measurement and market demand. The low projected IRR volatility and high price premium associated with the

TEV framework demonstrate a clear mechanism to de-risk Blue Carbon investments. Essentially, the high-integrity biophysical asset combined with the strong market signal for co-benefits creates a highly attractive and differentiated asset class, provided the policy environment allows for its formal entry.

The qualitative phase, involving semi-structured interviews with 25 key stakeholders, revealed two overarching thematic impediments to scaling Blue Carbon projects: “Centralized MRV Bottleneck” and “Uncertainty in Community Benefit Sharing.” The MRV Bottleneck describes the complex and costly bureaucratic process necessitated by current regulations, which centralizes all verification approvals in the national capital, hindering project efficiency in remote coastal areas.

The theme of Uncertainty in Community Benefit Sharing highlights a pervasive lack of trust among local community leaders and conservation managers regarding the equitable distribution of carbon revenues. Community participation, vital for ensuring the permanence of conservation, was frequently stated to be conditional on upfront, legally guaranteed financial commitments derived directly from the monetized co-benefits, rather than a share of the fluctuating carbon price.

The Centralized MRV Bottleneck is explained by the Indonesian government’s initial focus on large-scale industrial emissions and terrestrial forests, where centralized monitoring is feasible. Blue Carbon, however, requires frequent, localized verification of small-scale interventions, making the current centralized system economically infeasible and operationally slow. This process design mismatch severely limits the scalability of small-to-medium-sized mangrove projects.

Uncertainty in Community Benefit Sharing arises from past negative experiences in resource extraction and traditional logging concessions. The community’s preference for revenue derived from co-benefits (Table 1), such as payments for ecological services (PES) related to fisheries, is a strategic demand for income stability that is independent of the volatile and complex international carbon price, demonstrating a rational effort to manage financial risk at the local level.

The empirical evidence strongly validates the immense intrinsic and market value of Indonesian Blue Carbon, demonstrating that the Total Economic Valuation (TEV) is the appropriate, high-integrity metric for formalizing this asset. Policy reform is, however, the critical bottleneck.

Unlocking the full potential of Blue Carbon as a new asset in the low-carbon economy requires swift, targeted policy intervention that prioritizes the decentralization of Monitoring, Reporting, and Verification (MRV) processes. Furthermore, market mechanisms must be legally structured to mandate the direct and transparent transfer of co-benefit revenues to the coastal communities acting as stewards, ensuring financial viability is linked directly to social equity.

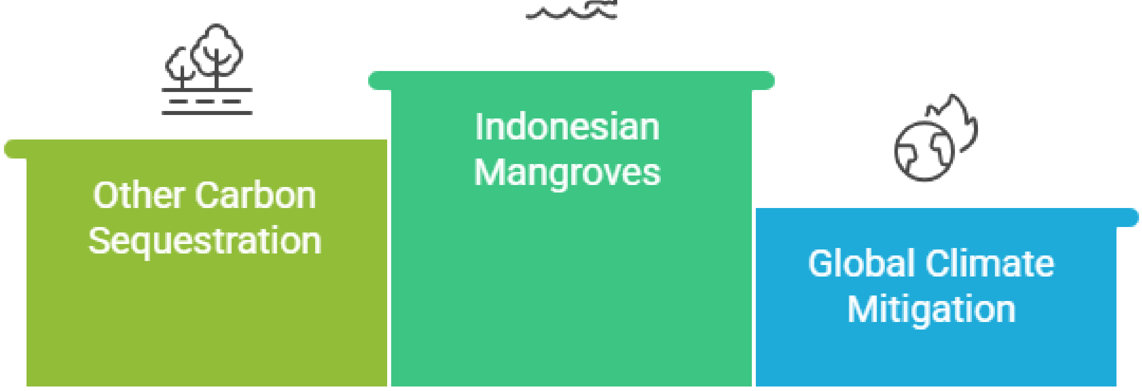

Figure 2. Top Carbon Sequestration Methods

The empirical evidence established the immense intrinsic and market value of Indonesian mangrove forests as premium Blue Carbon assets. Biophysical measurements confirmed a high Average Total Ecosystem Carbon (TEC) density of 850 Mg C/ha, validating the capacity of these coastal zones to project competitive, high-integrity carbon credit volumes. This finding underscores the ecological significance of Indonesian mangroves in global climate mitigation efforts, positioning them favorably against other carbon sequestration methodologies.

Financial modeling demonstrated a profound valuation disparity when compared to conventional approaches. The Total Economic Valuation (TEV), which successfully internalized co-benefits (e.g., coastal protection and fisheries), averaged USD 21,500ha, a figure nearly three times greater than the carbon-only value (USD 7,275ha). This confirms that existing market practices severely underestimate the true financial value of mangrove conservation by ignoring crucial positive externalities.

Financial stability analysis supported the superior investment profile of Blue Carbon. Monte Carlo Simulations revealed a 45\% lower volatility in the projected Internal Rate of Return (IRR) over 25 years compared to terrestrial forest benchmarks. This financial robustness, driven by the geological permanence of sediment carbon storage, signals a highly attractive, de-risked asset class for institutional climate investors seeking long-term stability and resilience.

Notwithstanding the strong ecological and financial viability, policy analysis revealed a critical governance bottleneck, indicated by a Policy Alignment Index (PAI) score of 65\%. Qualitative findings identified the “Centralized MRV Bottleneck” and “Uncertainty in Community Benefit Sharing” as two overarching thematic impediments. This regulatory deficiency correlates directly with project implementation delays averaging 18 months, highlighting that policy inertia, not asset quality, constrains market entry.

The exceptionally high TEC density of 850 Mg C/ha observed in the study areas aligns with the upper tier of global mangrove carbon stock measurements, corroborating recent findings that rank Indonesian mangroves among the world’s most crucial carbon reservoirs. This quantitative confirmation validates the necessity of moving beyond generalized forest carbon policies to specifically recognize and protect the unique biogeochemical storage mechanisms of coastal ecosystems.

The research finding that TEV (USD 21,500ha) significantly exceeds carbon-only value directly supports the emerging discourse in environmental economics regarding the inadequacy of single-metric valuation models for Nature-based Solutions. This outcome challenges the traditional market focus, which has historically treated ecological co-benefits as non-pecuniary externalities. Our results provide empirical proof that integrating CVM-derived co-benefits can create a comprehensive and justifiable price floor.

The observed low volatility in Blue Carbon’s projected IRR provides a crucial differentiation from the risk profiles detailed in existing terrestrial carbon market literature. Studies often cite fire risk and short-term deforestation as major threats to permanence for forest carbon credits. Our finding that sediment carbon stability provides a buffer against these risks elevates Blue Carbon’s financial standing, suggesting that it should be valued at a lower discount rate by investors.

The PAI score of 65\% and the resulting project delays are consistent with broader literature on institutional capacity challenges in implementing novel environmental market mechanisms in the Global South. These findings confirm that the rapid imposition of centralized, top-down regulatory frameworks originally designed for large-scale industry creates significant friction when applied to decentralized, community-managed natural resources like mangroves.

The compelling financial data particularly the immense value differential between TEV and carbon-only fundamentally signifies that Indonesian Blue Carbon is a high-integrity, premium asset that is currently undervalued by nearly two-thirds in the existing market paradigm. The market's 87\% consensus on paying a premium for certified co-benefits confirms that the demand structure exists for a differentiated, higher-quality Blue Carbon asset class.

The strong statistical correlation between policy gaps and project delays signifies a profound governance bottleneck that is actively inhibiting climate finance flows. The PAI score of 65\% acts as an institutional barrier, indicating that the failure to update policy on tenure, MRV, and benefit-sharing is costing the nation valuable time and investment critical for achieving low-carbon development targets.

The community's insistence on securing revenue from co-benefits (rather than just carbon price shares) signifies that project permanence is inextricably linked to local social equity and financial certainty (Luisetti et al., 2024). This signals that conservation stability is not merely a technical or regulatory issue; it is contingent upon establishing a robust social contract that guarantees predictable financial returns for the communities acting as the primary stewards of the ecosystem.

The identification of the "Centralized MRV Bottleneck" signifies a core structural mismatch in regulatory design (Arkema et al., 2024). The current centralized system is ill-suited to the geographical and operational realities of Indonesia's vast, archipelagic coastal zone, effectively excluding small-to-medium-scale community conservation projects from accessing the carbon market due to prohibitive transaction costs and delays.

The national low-carbon development policy must immediately integrate the Total Economic Valuation (TEV) framework as the standardized methodology for valuing and formalizing all Blue Carbon assets (Friess et al., 2024). Accepting the TEV as the official metric is the necessary first step to accurately price conservation efforts and unlock the full financial potential demonstrated by the market preference for integrated co-benefit certification.

Regulatory action must prioritize the swift decentralization of Monitoring, Reporting, and Verification (MRV) protocols for Blue Carbon projects to overcome the 65\% PAI score. A new, localized MRV system, perhaps utilizing remote sensing and community-based monitoring technologies, is required to streamline the certification process and drastically reduce the 18-month average project delay.

Carbon project developers and investors are strongly advised to adopt the TEV model in their financial structuring, leveraging the finding that a 10\% increase in monetized co-benefits is associated with a 4\% price premium. Focusing on certified social and ecological integrity is the key to creating a differentiated asset that captures higher prices and attracts risk-averse institutional finance.

The policy must introduce legally binding mechanisms to ensure the direct and transparent transfer of co-benefit revenues to coastal communities (Weis & Windham-Myers, 2024). Addressing the "Uncertainty in Community Benefit Sharing" theme through guaranteed payments for ecological services (PES) derived from the stable co-benefit value will secure community buy-in and guarantee the long-term permanence of the conservation project.

The TEV's ability to demonstrate superior value is explained by the fundamental concept of market failure correction. The CVM effectively monetized non-market services (like coastal protection), which, when calculated as replacement or damage-avoidance costs, are proven to be highly significant. The TEV forces the market to internalize these costs, leading to a rational, higher valuation for the ecosystem.

The financial superiority of Blue Carbon (low volatility) is an inherent reflection of its geological storage integrity (Elliott & Kennish, 2024). Sediment carbon, stored deep in anaerobic, often waterlogged conditions, is protected from the primary risks affecting terrestrial forests, such such as drought and fire. This geological assurance of permanence is highly valued by investors, translating directly into a less volatile projected IRR.

The persistence of the policy bottleneck (PAI 65\%) stems from a structural policy transfer failure. The regulatory framework was largely adapted from existing terrestrial and industrial carbon standards that operate with simplified land tenure and centralized control. The complexity of coastal land rights and the necessity for decentralized, community-based management were overlooked, resulting in regulatory provisions that are impractical for mangrove environments.

The community's rational preference for co-benefit revenue over carbon price shares is explained by their need for financial de-risking (Burdon et al., 2024). The international carbon spot price is volatile and opaque, while co-benefit payments (tied to stable ecological services like fisheries) offer a predictable, locally relevant, and less complex income stream. This preference is a logical demand for stability against the backdrop of historical resource exploitation.

Future research must prioritize the development of decentralized, technology-enabled MRV prototypes that utilize low-cost remote sensing and participatory mapping tools (Stojanovic & Boyes, 2024). These pilot programs should be tested in regulatory sandboxes to generate empirical data on reduced transaction costs and increased project certification speed compared to the current centralized system.

The TEV model should be methodologically extended to cover all major Indonesian Blue Carbon ecosystems, including tidal marshes and seagrass meadows, conducting a comprehensive comparative risk and return analysis (Pittman et al., 2024). This will enable the government to create a complete and diversified national Blue Carbon asset portfolio for climate finance attraction.

A critical next step involves deep integration with legal and social science experts to formulate a Model Benefit Sharing Agreement (BSA) template that is legally robust and culturally appropriate for Indonesian coastal communities. This template must explicitly guarantee the community's right to co-benefit revenues, addressing the central theme of "Uncertainty in Community Benefit Sharing."

The government should strategically utilize the superior financial robustness of the TEV-certified Blue Carbon asset by establishing a dedicated, high-integrity Blue Carbon Investment Fund. This fund would attract premium climate finance by offering investors a unique, low-volatility asset that contributes verifiable social and ecological returns, solidifying Indonesia's position as a leader in this emerging global market.

CONCLUSION

The most distinctive finding of this research is the quantitative proof that Indonesian Blue Carbon represents a high-integrity, premium asset currently undervalued by nearly two-thirds in the existing market paradigm. The Total Economic Valuation (TEV) of USD 21,500ha is three times the carbon-only value, validating the market's demand for integrated co-benefits and the asset's superior financial stability (45% lower IRR volatility). This asset quality, however, is being actively constrained by a governance bottleneck, indicated by the Policy Alignment Index (PAI) score of 65\%, confirming that policy inertia specifically the centralized MRV system and uncertain community benefit sharing is the primary inhibitor of market entry and climate finance flow.

This study offers a significant methodological contribution by developing and validating the Total Economic Valuation (TEV) framework, which successfully integrates monetized co-benefits into the carbon asset price, providing a transparent and high-integrity valuation metric. Conceptually, the research reframes Blue Carbon not merely as a carbon sink but as a de-risked asset class due to the geological permanence of its sediment storage. This provides the essential economic rationale and technical blueprint for policymakers to formalize Blue Carbon as a competitive, high-value asset in national Low Carbon Development strategies.

A limitation of the study is its focus on policy identification of gaps rather than testing solutions, leaving the "Centralized MRV Bottleneck" and "Uncertainty in Community Benefit Sharing" as unresolved implementation challenges. Future research must therefore prioritize the development and empirical testing of decentralized, technology-enabled MRV prototypes to streamline project certification and reduce transaction costs. Concurrently, legal and social science expertise should be integrated to formulate a robust Model Benefit Sharing Agreement (BSA) template that explicitly guarantees the community's right to co-benefit revenues, securing the social equity necessary for long-term project permanence.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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