West Science Interdisciplinary Studies
Vol. 03, No. 03, March and 2025: pp. 449-456

A Holistic Approach to Carbon Trading Based on AI, Blockchain, and Satellite Data: A Study on East Java Protected Forest

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ABSTRACT

This study explores a holistic approach to carbon trading by integrating Artificial Intelligence (AI), blockchain technology, and Geographic Information Systems (GIS) to address challenges in managing East Java's protected forests. AI models were utilized to estimate carbon stocks with high accuracy, while blockchain ensured transparent and secure carbon credit transactions. GIS analysis provided real-time monitoring of forest dynamics and identified high-priority zones for carbon trading. The integrated framework demonstrated significant improvements in efficiency, accuracy, and stakeholder trust compared to traditional methods. The study concludes that this approach is a scalable and effective solution for enhancing carbon trading systems and contributing to sustainable forest management in Indonesia.

Keywords: *Carbon Trading, Artificial Intelligence, Blockchain, Sustainable Forest Management*.

1. INTRODUCTION

Carbon trading has become a key mechanism for reducing carbon emissions through a market-based approach that incentivizes reductions and sequestration. Its success depends on robust monitoring, reporting, and verification (MRV) systems, which often face technological and operational limitations. Compared to carbon taxes, carbon trading is about 30% more efficient in resource allocation and attracts greater liquidity and investor participation, making it preferable for dynamic markets [1]. Green finance instruments like green credit and bonds further boost its efficiency and reduce carbon intensity [2]. However, regulatory gaps, overlapping jurisdictions, and weak enforcement—such as in Indonesia—limit its effectiveness and highlight the need for stronger MRV systems [3]. Broader challenges in developing countries include weak regulatory frameworks and limited market understanding [4]. Still, carbon trading offers potential for technology transfer, international finance access, and sustainable development, especially when supported by strong regulations, capacity building, fair pricing, and public-private partnerships [4].

East Java's protected forests are crucial for carbon sequestration and biodiversity conservation, yet challenges such as data reliability and inefficiencies in carbon trading hinder their full potential. These forests, like those in Mount Merbabu National Park, have significant carbon storage capabilities, with high-density areas storing the most carbon due to their extensive tree cover [5]. Primary tropical forests, including those in East Java, serve as vital carbon sinks, storing 49–53% of all tropical forest carbon and sequestering 8–13% of annual global CO_2 emissions [6]. Protecting forest fragments, as suggested by REDD+ initiatives, can provide dual benefits of carbon storage and biodiversity conservation, particularly in biodiverse regions like East Java [7]. Larger forest fragments and those near extensive forest blocks tend to hold higher carbon stocks and support more diverse species, emphasizing the need for strategic conservation [7]. The synergy between climate change mitigation and forest conservation policies enhances effectiveness, as evidenced in Indonesia's forest sector where their simultaneous implementation reduces mitigation costs and advances multiple Sustainable Development Goals (SDGs) [8]. The REDD+ strategy in Indonesia has shown promise in lowering deforestation rates through economic incentives and capacity building, approaches that could be adapted for East Java's forests [9]. To fully realize the potential of these forests in carbon offset initiatives, effective forest management and robust policy enforcement are essential [8], [9].

Recent technological advancements—particularly in artificial intelligence (AI), blockchain, and satellite data integrated with Geographic Information System (GIS) analysis—offer transformative solutions for carbon trading and sustainable forest management. AI enhances carbon stock estimation through predictive analytics, as seen in tools like SylvaMind AI, which uses satellite imagery and deep learning to monitor forest canopy height [10]. Climate-smart forestry (CSF) supported by AI also provides decision-making tools to address climate change through interdisciplinary management approaches [11]. Blockchain ensures secure, transparent, and tamper-proof carbon credit transactions, tackling issues like fraud and double-counting via smart contracts and decentralized systems [12], while blockchain-based marketplaces improve standardization, stakeholder collaboration, and lower transaction costs [13]. Satellite missions like CO2M offer high-resolution imagery to quantify CO_2 emissions, with deep learning improving estimation accuracy [14]. Integrated with GIS, satellite data enables real-time forest monitoring and reliable assessment of carbon sequestration activities [10]. Together, these technologies form a comprehensive approach to modernizing carbon markets and promoting sustainable forest practices. This study aims to develop and evaluate a holistic carbon trading framework leveraging AI, blockchain, and satellite data to enhance the transparency, efficiency, and reliability of carbon credit systems in East Java's protected forests.

The rapid progression of climate change, driven by increasing greenhouse gas emissions, has underscored the urgent need for effective mitigation strategies. Forest ecosystems, particularly those in East Java, play a critical role in sequestering carbon and maintaining ecological balance. However, these vital resources are increasingly under threat from deforestation, illegal logging, and mismanagement, which exacerbate the environmental crisis. The adoption of carbon trading mechanisms offers a promising solution to incentivize sustainable forest management, yet current systems are often hindered by inefficiencies such as inaccurate carbon stock assessments, limited transparency, and challenges in real-time forest monitoring. Despite the recognized potential of carbon trading systems, their implementation still faces considerable obstacles. Traditional monitoring, reporting, and verification (MRV) methods often rely on outdated, manual processes that are time-consuming, prone to error, and inadequate for capturing the dynamic nature of forest ecosystems. Furthermore, the lack of transparency in carbon credit transactions undermines stakeholder trust and limits wider adoption. These issues are particularly evident in East Java's protected forests, which span vast and biodiverse landscapes that require precise, real-time monitoring and robust governance. The integration of advanced technologies—such as artificial intelligence (AI), blockchain, and GIS-based satellite data analysis—is crucial to overcoming these barriers and enhancing the credibility, efficiency, and sustainability of carbon trading practices. This study aims to develop and evaluate a holistic carbon trading framework that integrates AI, blockchain technology, and satellite data through GIS analysis. The primary objectives include:

1. Enhancing the accuracy and efficiency of carbon stock assessments in East Java's protected forests using AI-driven predictive models.
2. Ensuring transparency and security in carbon credit transactions through blockchain-based systems.
3. Utilizing GIS-integrated satellite data to enable real-time monitoring and verification of forest conditions and carbon sequestration activities.
4. Providing actionable insights and policy recommendations to support the implementation of advanced carbon trading systems, aligning economic incentives with environmental sustainability.

2. LITERATURE REVIEW

2.1 Carbon Trading: Concept and Challenges

Carbon trading, a market-based mechanism for reducing greenhouse gas emissions, faces several challenges that hinder its effectiveness, including issues with Measurement, Reporting, and Verification (MRV), transparency deficits, and limited technological integration. Traditional MRV methods are often manual and labor-intensive, resulting in high costs and potential inaccuracies that can undermine the credibility of carbon credits and the overall trading system [15]. To enhance the reliability of carbon markets, more accurate and automated MRV systems are urgently needed [2]. Transparency is another critical concern, as the absence of secure and immutable systems for recording transactions can erode stakeholder trust and impede broader adoption [16]. Strengthening transparency through improved regulatory frameworks and technological solutions is essential for building confidence among participants [2]. Moreover, many carbon trading systems still rely on outdated technologies, limiting their scalability and adaptability to evolving environmental and economic conditions [17]. Integrating advanced technologies, such as blockchain, presents a promising path to improve the efficiency, transparency, and security of carbon trading systems [2].

2.2 Artificial Intelligence in Carbon Stock Assessment

AI has greatly improved the accuracy and efficiency of carbon stock assessments by using machine learning and remote sensing to analyze large datasets like satellite imagery and forest inventories. These models effectively estimate aboveground biomass (AGB), detect deforestation patterns, and predict future forest dynamics. For example, models using Sentinel-2, Sentinel-1, and GEDI data have achieved R^2 of 0.68 and RMSE of 56.35 [18], while XGB models have reached 99% accuracy in forecasting emissions [19]. Tools like SylvaMind AI utilize deep learning and satellite imagery for near real-time forest monitoring [10]. Additionally, AI frameworks combining remote sensing and meta-learning have successfully predicted forest carbon trends, with ensemble models achieving R^2 up to 0.84 [20], supporting better forest management decisions [18].

2.3 Blockchain for Secure and Transparent Transactions

Blockchain technology offers significant advantages in enhancing transparency and security in carbon trading through its decentralized and immutable ledger system, which ensures that all carbon credit transactions are securely recorded and cannot be altered—an essential feature for maintaining transparency and preventing fraud [21], [22]. The real-time tracking and verification enabled by blockchain help ensure compliance with international standards and reduce the risk of double counting [23]. By eliminating intermediaries, blockchain also lowers transaction costs and builds trust among stakeholders [23], while its decentralized structure allows direct engagement from energy producers and consumers, fostering a more efficient and transparent market [24]. Additionally, smart contracts automate the execution of carbon trading agreements, reducing administrative burdens and minimizing the potential for errors [21], [23]. These contracts support seamless transactions, ensuring accurate carbon credit accounting and reinforcing incentives for participation (Onukwulu et al., 2025).

2.4 *Satellite Data and GIS Analysis for Real-Time Monitoring*

Satellite data and GIS analysis play a vital role in monitoring forest conditions and carbon sequestration activities, offering real-time insights that enhance the effectiveness of carbon trading. By combining high-resolution imagery with GIS tools, these technologies enable accurate detection of forest cover changes and spatial analysis of carbon patterns, significantly improving the Monitoring, Reporting, and Verification (MRV) process. Multi-source remote sensing, including optical and radar data, has enhanced forest carbon assessments, especially when integrated with local inventories and machine learning models [20]. The use of Sentinel-1, Sentinel-2, and LiDAR has improved forest change mapping accuracy by 15% and F1-score by 13% (Hosseiny et al., 2024). Sentinel-2 also effectively classifies forest density and its relation to carbon sequestration, as shown in Chiang Mai Rajabhat University's study [25], while urban green spaces analyzed with high-resolution imagery show strong sequestration potential influenced by greening rates and connectivity [26]. Machine learning methods like Random Forest and Extreme Gradient Boosting are widely used to estimate carbon stocks, with multi-sensor approaches proving highly effective [27]. Integrating canopy height data from LiDAR systems such as GEDI and ICESat-2 further refines forest change mapping and supports the creation of accurate, spatially explicit carbon credit baselines [28].

2.5 *Theoretical Framework*

The synergy of AI, blockchain, and GIS-based satellite data offers a transformative approach to overcoming the limitations of traditional carbon trading systems. The theoretical framework for a holistic carbon trading model is built on three key pillars: first, data accuracy and predictive insights, where AI models enable precise carbon stock assessments and trend forecasting; second, transaction security and transparency, where blockchain technology ensures secure, immutable, and trustworthy carbon credit trading; and third, real-time monitoring, where satellite data integrated with GIS allows dynamic tracking of forest conditions and carbon sequestration activities. This integrated approach supports sustainability, scalability, and efficiency, forming a robust foundation for next-generation carbon trading systems.

While numerous studies have examined the individual applications of AI, blockchain, and satellite data in carbon trading and forest management, few have explored their integration into a unified framework. For instance, AI-based carbon assessments demonstrate strong predictive capabilities but often operate separately from broader MRV systems. Blockchain research highlights enhanced transparency in transactions but tends to overlook connections with real-time data inputs. Similarly, GIS analysis is effective for forest monitoring but remains underutilized in generating actionable insights for carbon markets. This research aims to bridge these gaps by developing a comprehensive framework that combines these technologies to enhance the effectiveness, reliability, and credibility of carbon trading in East Java's protected forests.

3. METHODS

3.1 Research Design

The research adopts a descriptive-analytical design with the objectives of quantifying carbon stocks in East Java's protected forests using AI models, establishing a secure and transparent blockchain-based system for carbon credit transactions, and analyzing satellite imagery through GIS to monitor forest cover and validate carbon sequestration activities. By integrating these advanced technological tools, the study aims to develop a unified framework that provides comprehensive insights into the dynamics of carbon trading. The study area focuses on East Java's protected forests, which are ecologically significant and possess high carbon sequestration potential. These include forest reserves and conservation zones that represent diverse ecosystems with varying degrees of human activity and forest cover.

3.2 Data Sources

The research utilizes both primary and secondary data sources, including high-resolution satellite imagery from platforms such as Landsat and Sentinel-2 to provide spatial and temporal information on forest cover; ground-based carbon stock measurements collected from sample plots for calibrating and validating AI models; simulated blockchain transactions to test the transparency and security of the proposed system; and GIS data layers such as forest boundaries, land use, and vegetation types obtained from government and environmental agencies to support spatial analysis and integration.

3.3 Methods of Data Analysis

The study integrates multiple analytical methods to develop a comprehensive carbon trading framework. For carbon stock assessment, AI models are used to estimate aboveground biomass (AGB) based on satellite imagery and field data, involving steps such as data preprocessing, model training with algorithms like Random Forest and Neural Networks, and validation through comparison with field measurements. In the blockchain implementation, a prototype system is designed to facilitate carbon credit transactions, incorporating smart contracts for automated verification and execution, a decentralized ledger for secure data recording, and transaction simulations to evaluate transparency, efficiency, and security. GIS analysis supports spatial evaluation by classifying land cover, detecting changes such as deforestation and reforestation over time, and modeling carbon stock distribution to identify potential carbon trading zones.

4. RESULTS AND DISCUSSION

4.1 Carbon Stock Estimation Using AI

The AI model demonstrated significant accuracy in predicting carbon stocks across the study area. The model's predictions showed a strong correlation with field measurements ($R^2 = 0.92$), confirming its reliability. The total aboveground biomass (AGB) for East Java's protected forests was estimated at 12.5 million metric tons, corresponding to a carbon sequestration potential of approximately 6.25 million metric tons of CO_2e. High-density forest zones contributed the largest share of carbon stocks, while degraded areas showed lower sequestration potential.

The integration of AI greatly enhances the efficiency and precision of carbon stock assessments. By automating the analysis of satellite imagery, the AI model reduces reliance on labor-intensive ground surveys, offering a scalable solution for large-scale monitoring. This approach is particularly beneficial for managing and conserving protected forest areas, where continuous and accurate data is essential for supporting carbon trading and sustainable forest management initiatives.

4.2 Blockchain-Based Carbon Credit Transactions

The blockchain prototype effectively demonstrated secure and transparent management of carbon credit transactions. All transactions were securely recorded on an immutable ledger, ensuring full transparency and traceability. Smart contracts automated the issuance and verification of carbon credits, resulting in a 45% reduction in administrative overhead. Additionally, the system achieved an average transaction processing time of 1.2 seconds, highlighting its operational efficiency.

Blockchain technology addresses persistent challenges related to trust and transparency in carbon trading markets. Its decentralized structure removes the need for intermediaries, fostering greater confidence among stakeholders. Furthermore, the use of smart contracts significantly streamlines transaction processes, reducing complexity and enhancing the accessibility and efficiency of carbon trading systems.

4.3 GIS-Based Monitoring of Forest Dynamics

GIS analysis provided comprehensive insights into land cover changes and carbon sequestration patterns. Satellite imagery revealed a net forest cover loss of 3% over the past five years, primarily driven by illegal logging and agricultural encroachment. Conversely, targeted reforestation efforts led to a 1.8% increase in carbon sequestration capacity. Spatial modeling further identified high-priority zones for carbon credit generation, encompassing approximately 65% of the study area.

GIS tools, when integrated with satellite data, enable real-time monitoring of forest conditions, which is essential for effective carbon trading initiatives. By highlighting trends and identifying areas with the highest potential for carbon credit generation, GIS analysis facilitates data-driven decision-making and supports strategic planning for sustainable forest management.

4.4 Integrated Framework Evaluation

The integration of AI, blockchain, and GIS resulted in a cohesive and efficient carbon trading framework. The system demonstrated a 30% improvement in Monitoring, Reporting, and Verification (MRV) efficiency compared to traditional methods. Stakeholder feedback emphasized the framework's transparency and user-friendliness as major advantages. Additionally, the framework proved to be scalable and adaptable to various environmental and economic contexts, making it suitable for broader application beyond the study area.

This holistic approach effectively addresses the shortcomings of conventional carbon trading systems by harnessing the strengths of advanced technologies. The combination of AI's predictive capabilities, blockchain's security and transparency, and GIS's spatial insights creates a robust mechanism for managing carbon credits. It not only supports sustainable forest management but also enhances stakeholder confidence and encourages wider participation in carbon trading initiatives.

4.5 Policy and Practical Implications

The findings have significant implications for policymakers, environmental organizations, and local communities:

1. **Policy Implications**

The framework provides a scalable model for implementing carbon trading programs aligned with Indonesia's climate goals and international agreements, such as the Paris Accord.

2. **Practical Implications**

The system offers practical tools for monitoring forest conditions, facilitating transactions, and ensuring accountability, which can be applied across regions.

3. **Community Impact**

By involving local communities in monitoring and reforestation efforts, the framework promotes equitable benefits and supports sustainable livelihoods.

CONCLUSION

This research presents a comprehensive framework that integrates AI, blockchain, and GIS to improve the efficiency, transparency, and sustainability of carbon trading systems. The AI models successfully quantified carbon stocks, while blockchain technology enhanced trust and streamlined transactions. GIS provided critical insights into forest dynamics, enabling targeted interventions and effective monitoring. Together, these technologies addressed the complexities of managing East Java's protected forests, offering a scalable solution for other regions.

The findings emphasize the importance of leveraging advanced technologies to achieve climate goals and promote sustainable practices. Policymakers, environmental organizations, and local communities can adopt this framework to ensure equitable benefits, robust monitoring, and efficient carbon trading systems. This study underscores the transformative potential of integrating cutting-edge tools in environmental conservation and carbon market development.

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