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Integration of Satellite and Blockchain Technology in Carbon Trade Marketing Model: Case Study of REDD+ Scheme in Bromo-Tengger-Semeru Protection Forest

Haryono
Universitas Bhayangkara Surabaya

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ABSTRACT

This study explores the integration of satellite technology and blockchain platforms in the context of the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) program of the Bromo-Tengger-Semeru Protection Forest. Through Geographic Information Systems (GIS) spatial analysis and blockchain modeling, the research develops a comprehensive carbon trade marketing model to address monitoring, transparency, and efficiency problems in carbon credit trade. Results indicate that GIS effectively identifies high-priority sites for conservation, while blockchain enables and maximizes carbon credit trade with smart contracts. Stakeholder comments underscore regulatory clarity, public engagement, and technical expertise in ensuring the optimal utilization of the model. The proposed convergence offers a cost-effective, scalable, and open-source solution to complement REDD+ implementation for promoting global efforts toward mitigation of climate change and sustainable development.

Corresponding Author:

Name: Haryono
Institution: Universitas Bhayangkara Surabaya
Email: haryono@ubhara.ac.id

1. INTRODUCTION

Climate change is now among the most pressing concerns of the 21st century, and it needs innovative solutions to mitigate its impacts on ecosystems, economies, and societies. Carbon trading is among the most important measures in addressing this global concern, as it facilitates the monetization of carbon sequestration activities using market-based instruments [1]–[3]. Among these, the REDD+ mechanism has fallen into prominence, especially in those nations with high forest cover density like Indonesia. Bromo-Tengger-Semeru Protection Forest is an exemplary case study due to its ecological importance along with carbon sequestration capacity within the REDD+ mechanism.

While promising, the REDD+ scheme is plagued by inefficiencies such as ineffective monitoring, a lack of transparency, and a poor level of trust among stakeholders. Carbon stock estimation and credit trading have conventionally been plagued by inaccuracies, fraud, and logistical inefficiency. These challenges underscore the necessity for technology integration to raise the credibility and efficiency of carbon trading mechanisms.

Satellite technology and blockchain have also emerged as groundbreaking tools with the ability to change carbon trade systems. Satellite technology enables real-time, high-resolution monitoring of carbon stocks in the forest, while blockchain offers incorruptible and transparent carbon transactions records. Their combination can complement the gaps by providing credible evidence, enhanced accountability, and stakeholder confidence in carbon markets.

The escalating impacts of climate change, including rising global temperature, extreme weather events, and loss of biological diversity, bring into sharp focus the imperative need for immediate and effective mitigation measures. Forests as natural carbon sinks of atmospheric carbon dioxide play a vital role in preventing greenhouse gas emissions, thereby an integral part of achieving net-zero emissions globally [4]–[6]. REDD+ policy, which offers incentives for forest conservation and its sustainable use, has emerged as an essential tool in reducing deforestation and the resulting greenhouse gas emissions.

However, the effectiveness of REDD+ projects relies greatly on accurate monitoring, verification, and transparency of carbon stock estimations and credit transactions. Traditional approaches applied for these ends are incomplete, flawed, and susceptible to tampering, undermining the credibility of carbon trading systems. With the necessity to meet global climate objectives under pressure, new technologies are in dire need to address these issues and offer reliability and scalability to carbon trade systems.

Satellite technology and blockchain is a unique chance to transform carbon trading systems. Satellite images can provide timely and precise information on forest health, and blockchain offers secure, transparent, and tamper-evident carbon credit transaction records. Their use in the Bromo-Tengger-Semeru Protection Forest, a ecologically significant forest in Indonesia, can serve as a model for other REDD+ initiatives around the world. The window of opportunity is to leverage these innovations to enhance carbon trading, promote sustainable forest management, and contribute meaningfully to global climate action.

Despite its promise, the application of the REDD+ program to Indonesia is strongly confronted by outstanding issues that disqualify its efficacy, ranging from inaccurate carbon monitoring based on old forest carbon stock estimation measures with limited use of field-based data to compromised carbon trading platform transparency that fuels the potentiality of fraudulent mechanisms and diminishes stakeholders' level of trust. Also, sluggish and resource-costly verification protocols limit its utility, as does restricted stakeholder trust due to a lack of established systems in which carbon credits are tracked and authenticated. This study explores the integration of satellite technology and blockchain to develop a robust carbon trade marketing model, focusing on the REDD+ program in Bromo-Tengger-Semeru Protection Forest. Using Geographic Information System (GIS) analysis, the study identifies priority areas for carbon sequestration and carbon trade potential and demonstrates how blockchain can secure and automate carbon credit transactions.

The objectives of this study are threefold:

1) To determine the current constraints and challenges to the use of REDD+ in the Bromo-Tengger-Semeru Protection Forest.
2) To investigate the role of satellite technology in helping improve carbon stock estimation and monitoring.
3) To show how blockchain can boost transparency and accountability in carbon trading systems.

2. LITERATURE REVIEW

2.1. Carbon Trading and the REDD+ Scheme

Carbon trading, particularly through mechanisms like REDD+, plays a significant role in mitigating global climate change by encouraging forest conservation and carbon sequestration. However, the use of such schemes is hindered by severe challenges that make them ineffective. Studies indicate that there are few monitoring systems that are robust enough, and therefore the validity of carbon credits issued is in doubt with less than 16% of carbon credits from various projects representing actual emission reduction [7]. In addition, decreased transparency in operations within projects and transactions involving carbon credits raises doubts regarding the legitimacy of the carbon market [8]. The expense of carbon credit verification is high, and this discourages engagement, particularly in developing countries where resources are scarce [9]. The remedies to the aforementioned challenges include digital technologies simplifying carbon emissions to be easier and more efficient to monitor [10] and integrating biodiversity insurance with carbon credits to mitigate risks and guarantee enhanced project resilience, translating into enhanced environmental performance [8].

2.2. The Role of Satellite Technology in Forest Monitoring

Satellite technology takes center stage in forest monitoring and carbon stock assessment, leveraging high-resolution remote sensing to optimize efficiency and precision. Multiple platforms like Landsat, Sentinel, and LiDAR provide vital information to track forest change, facilitating precise estimation of biomass and carbon storage. This intersection of technologies not only exceeds traditional methods but also enables deforestation and degradation tracking in real-time, a major determinant of the success of conservation efforts like REDD+. Satellite-based methods, such as the LandTrendr algorithm, achieve good performance (Kappa coefficient of 0.79) in detection of forest disturbance [11]. Additionally, integration of optical, LiDAR, and SAR data significantly improves the accuracy of carbon stock estimation (R^2=0.68) [12], [13]. Advanced machine learning techniques, including Extreme Gradient Boosting, also maximize the predictive effectiveness of forest characteristics from satellite imagery [14], [15]. Near real-time detection of deforestation facilitates timely actions (Hosseiny et al., 2024), while the integration of GIS with satellite imagery supports effective forest management and carbon credit generation, particularly in protected forests [11].

2.3. Blockchain Technology in Carbon Trading

Blockchain technology offers a groundbreaking way of enhancing transparency and trust in carbon trading systems by utilizing a decentralized and unalterable ledger to assist in addressing critical issues such as fraudulent reporting, double counting of credits, and less efficient verification processes. The use of smart contracts also automates transactions, reducing administration costs and improving business efficiency. Blockchain provides a tamper-resistant, time-stamped record of all transactions, ensuring accountability and preventing manipulation [16], and also allowing stakeholders to trace the source and life cycle of carbon credits, ensuring trust between buyers and sellers [17]. Additionally, advanced visualization techniques simplify transaction history, making it easier to identify fraudulent transactions [18], and blockchain's non-reversibility reduces double counting threats, enhancing global standard compliance [18]. Practical uses such as the Climate Warehouse of the World Bank and the CarbonX platform demonstrate the scalability and use of blockchain across different carbon models of trading [17], while its use in the aviation industry to trace carbon footprint demonstrates its utility across sectors [19].

2.4. Integrating Satellite and Blockchain Technology in Carbon Trade Models

Intersecting satellite and blockchain technologies offers a game-changer in mitigating flaws of current carbon trading systems as satellite technology enhances accuracy of carbon stock inventory while blockchain ensures safe, transparent, and genuine transactions. This intersection not only prevents human error but also facilitates credibility of carbon markets with easy trading processes. Satellite imagery allows real-time carbon stock monitoring, increasing the accuracy of carbon credit quantifications [17], and supports tracking forest cover and changes in carbon sequestration, which is imperative for REDD+ initiatives [20]. Blockchain technology also improves the system by creating a tamper-proof record for carbon credit transactions, reducing fraud and double counting [21], and smart contracts simplify the trading process, and all transactions are transparent and verifiable [18]. The actual application of this integrated model in the Bromo-Tengger-Semeru Protection Forest can ensure better efficiency for carbon trading and support sustainable forest management [17], [20], with firm direction for stakeholders to effectively implement global climate goals.

2.5. Case Studies of Technological Integration in Carbon Markets

The successful application of technology in carbon trading is exemplified through varied projects that utilize advanced monitoring systems and blockchain, illustrating how innovative approaches can enhance transparency, efficiency, and effectiveness in environmental protection and carbon offsetting. Norway's partnership with Brazil employed satellite imagery to monitor deforestation in the Amazon, where the DETER-RT system, combining Synthetic Aperture Radar (SAR) and optical data, significantly improved detection rates and response times during high-season periods like the fire season [22]. The partnership achieved remarkable deforestation rate reductions, indicating the effectiveness of technology-driven monitoring systems. Similarly, the Canadian CarbonX platform uses blockchain technology to facilitate carbon offset transactions with traceability and transparency, building trust between parties, and maximizing trading activities [23]. Through blockchain, the platform enhances the integrity of the activities of carbon trading. Additionally, Indonesia's Peatland Restoration Program utilizes GIS-based satellite tracking to track peatland restoration, strengthening REDD+ ambitions and augmenting carbon sequestration [24], demonstrating the potential of integrating remote sensing technologies for effective environmental stewardship. The foregoing case studies underscore the viability and benefits of integrating cutting-edge technologies with carbon trading programs, holding important lessons for the Bromo-Tengger-Semeru Protection Forest.

2.6. Research Gaps

While existing literature highlights the potential of satellite and blockchain technologies in carbon trading, few studies have explored their combined application within the context of REDD+ initiatives. Furthermore, limited research has examined the specific challenges and opportunities associated with implementing these technologies in Southeast Asia, particularly in Indonesia.

This study seeks to address these gaps by developing an integrated satellite and blockchain-based carbon trade marketing model tailored to the REDD+ scheme in the Bromo-Tengger-Semeru Protection Forest. By leveraging GIS analysis, the research aims to provide actionable insights and contribute to the broader discourse on technology-driven solutions for climate change mitigation.

3. METHODS

3.1 Research Design

This study employs a mixed-methods approach, combining qualitative and quantitative techniques to develop and evaluate an integrated carbon trade marketing model based on satellite and blockchain technology within the context of the REDD+ scheme in the Bromo-Tengger-Semeru Protection Forest. The research utilizes Geographic Information Systems (GIS) for spatial analysis and blockchain simulations to demonstrate the effectiveness of the proposed model.

3.2 Study Area

The research focuses on the Bromo-Tengger-Semeru Protection Forest, a critical ecological zone in East Java, Indonesia. This area is part of the REDD+ initiative due to its high biodiversity value and significant carbon sequestration potential. Satellite data and field information are collected to monitor forest conditions, while blockchain simulations represent the carbon credit transactions generated from this region.

3.3 Data Collection Methods

Primary data includes field surveys, where ground-truthing exercises are conducted to validate satellite data on forest cover, biomass, and carbon stocks, and stakeholder interviews, which involve semi-structured discussions with key stakeholders such as government officials, local communities, and private sector participants to understand the challenges and opportunities of REDD+ implementation. Secondary data consists of satellite imagery from high-resolution sources like Landsat 8, Sentinel-2, and LiDAR to assess forest cover, carbon sequestration potential, and deforestation trends; blockchain protocols, where data from blockchain-based carbon trading platforms (e.g., Ethereum, Hyperledger) is analyzed to model the secure and transparent exchange of carbon credits; and literature review, which involves examining existing studies, policy documents, and REDD+ implementation reports to establish a theoretical foundation for the proposed model.

3.4 Data Analysis Methods

GIS analysis includes forest carbon stock assessment, where GIS-based tools process satellite imagery to calculate carbon stock in the Bromo-Tengger-Semeru Protection Forest using biomass estimation methods like allometric equations, and deforestation and degradation monitoring, which employs time-series satellite analysis to track forest cover changes and identify high-risk deforestation areas. Blockchain simulation covers transaction modeling, where blockchain simulations replicate carbon credit transactions through smart contracts that automate verification, validation, and trading, and system testing, which evaluates scalability, security, and efficiency using key performance indicators (KPIs) such as transaction speed, data integrity, and cost efficiency. Qualitative analysis consists of thematic analysis, which codes and examines stakeholder interview insights to identify recurring themes in REDD+ implementation, and policy gap analysis, which reviews secondary data to detect policy shortcomings and recommend solutions for integrating satellite and blockchain technologies.

4. RESULTS AND DISCUSSION

4.1. GIS Analysis of Forest Carbon Stocks

The GIS analysis revealed that the Bromo-Tengger-Semeru Protection Forest holds significant carbon sequestration potential. The study area was classified into three primary zones based on carbon stock levels: High Carbon Stock Areas (HCSA), covering 45% of the total area, characterized by dense forest cover with an average carbon storage of 150 tons per hectare; Moderate Carbon Stock Areas (MCSA), comprising 35% of the area, exhibiting mixed land-use patterns with carbon storage levels between 50 and 100 tons per hectare; and Low Carbon Stock Areas (LCSA), making up 20% of the area, where heavy degradation or deforestation has resulted in carbon storage levels below 50 tons per hectare.

Satellite imagery indicated a gradual decline in forest cover over the past decade, emphasizing the urgency of implementing REDD+ initiatives to mitigate deforestation and enhance carbon sequestration.

4.2. Blockchain Simulation Results

The blockchain simulation demonstrated the feasibility of using decentralized systems for carbon credit transactions. Key findings include improved smart contract performance, where the implementation of automated verification and validation processes reduced transaction times by 30%. Additionally, the system ensured data security, maintaining transparency and data integrity with no unauthorized modifications detected during the simulation.

The model also proved its scalability, successfully managing up to 10,000 transactions per second, highlighting its potential for large-scale carbon trading. Furthermore, the cost efficiency of the blockchain system was evident, as transaction fees were significantly lower compared to traditional methods, making it a viable and cost-effective alternative.

4.3. Stakeholder Feedback

Interviews with stakeholders revealed diverse perspectives on integrating satellite and blockchain technology in REDD+. Government officials expressed optimism about the potential for improved forest monitoring and greater transparency in carbon credit transactions. They highlighted how satellite imagery could enhance enforcement efforts and how blockchain technology could create an immutable record of carbon credits, reducing fraud and mismanagement. However, they also emphasized the need for robust governance frameworks to ensure seamless implementation.

Local communities, while acknowledging the benefits of enhanced monitoring, raised concerns about equitable benefit-sharing and the risk of exclusion from decision-making processes. They stressed the importance of capacity-building initiatives to empower indigenous and local populations to participate effectively in REDD+ programs. Private sector participants recognized the efficiency, security, and cost-effectiveness of blockchain systems but emphasized the necessity of clear regulations to support investment and scalability. They pointed out that while blockchain can streamline transactions and reduce fraud, regulatory uncertainties could hinder widespread adoption. Overall, stakeholders underscored the need for collaboration between governments, communities, and private entities to ensure the successful integration of these technologies in REDD+ initiatives.

4.4. Discussion

The GIS analysis underscores the critical role of spatial data in identifying high-priority areas for conservation and carbon credit generation. By providing accurate and real-time information on forest cover and carbon stocks, GIS tools enable stakeholders to make informed decisions and allocate resources effectively. However, the accuracy of GIS outputs depends on the resolution and quality of satellite imagery. Studies have highlighted that GIS facilitates the mapping and monitoring of forest resources, aiding in the identification of areas at risk and promoting conservation efforts [25]. Moreover, GIS plays a crucial role in improving the accuracy of forestry cadastre, which is essential for sustainable forest management [26]. Future advancements in remote sensing technology, such as the integration of high-resolution NDVI data from Sentinel satellites, could further enhance the reliability of GIS-based assessments [27].

The blockchain simulation highlights its transformative potential in addressing the inefficiencies of traditional carbon trading mechanisms. The decentralized nature of blockchain ensures transparency and minimizes the risk of fraud, while smart contracts streamline administrative processes. Previous research has emphasized that blockchain technology enhances the security and efficiency of environmental markets by ensuring tamper-proof record-keeping and automating transaction verification [28]. However, the adoption of blockchain requires significant investments in infrastructure and technical expertise. Collaborative efforts between governments, private sectors, and technology providers are essential to overcoming these barriers. Additionally, scalability remains a challenge, as blockchain networks must be capable of handling large-scale carbon credit transactions without compromising transaction speed or security.

The integration of GIS and blockchain technologies offers a comprehensive solution to the challenges of REDD+ implementation. While GIS provides the spatial data necessary for carbon accounting, blockchain ensures secure and efficient transactions of carbon credits. This synergy enhances the credibility of carbon trading systems and fosters trust among stakeholders. For example, real-time monitoring capabilities of GIS can be linked to blockchain-based smart contracts to automatically trigger payments upon achieving conservation targets, reducing administrative burdens and improving compliance. Previous studies suggest that such integration could significantly improve transparency and efficiency in carbon markets [29]. As advancements in remote sensing and blockchain technologies continue, their combined application in REDD+ programs could pave the way for more effective and scalable climate change mitigation strategies.

4.4.1 Addressing Challenges in REDD+ Implementation

The study identifies several challenges that must be addressed to ensure the successful integration of satellite and blockchain technology. A robust regulatory framework is essential to govern blockchain-based carbon trading and ensure compliance with international standards, providing legal clarity and fostering investor confidence. Community engagement is equally critical, as local communities must be actively involved in REDD+ activities to promote equitable benefit-sharing and enhance the long-term sustainability of conservation efforts. Additionally, technical capacity remains a key barrier, necessitating investments in training and capacity-building initiatives to equip stakeholders with the necessary skills to effectively utilize GIS and blockchain technologies. Addressing these challenges through policy development, inclusive participation, and capacity enhancement will be crucial for maximizing the potential of these technologies in REDD+ implementation.

4.4.2 Policy Implications

The findings have significant policy implications for scaling up REDD+ initiatives:

a) Governments should adopt policies that incentivize the adoption of blockchain technology and facilitate public-private partnerships.
b) International collaborations can provide technical and financial support to enhance the capacity of developing countries to implement advanced technologies.
c) Policies should prioritize the inclusion of local communities to ensure that the benefits of REDD+ activities are distributed equitably.

5. CONCLUSION

The integration of satellite and blockchain technology within the REDD+ framework presents a transformative solution for addressing deforestation and enhancing carbon trading efficiency. GIS tools offer robust spatial data for monitoring forest conditions and assessing carbon stocks, while blockchain systems ensure transparency, security, and scalability in carbon credit transactions. The synergy of these technologies supports the development of a comprehensive and sustainable carbon trade marketing model. Key findings from this study highlight that GIS analysis effectively identifies critical conservation areas with high carbon sequestration potential, aiding in resource allocation and prioritization. Additionally, blockchain simulations demonstrated the feasibility of secure, efficient, and cost-effective management of carbon credit transactions through smart contracts.

Stakeholder engagement further emphasized the need for regulatory frameworks, equitable benefit-sharing, and technical capacity-building to ensure successful implementation. This study underscores the importance of integrating advanced technologies to enhance REDD+ initiatives, providing a scalable and transparent approach to carbon credit management. By addressing existing challenges, the proposed model not only strengthens REDD+ implementation but also sets a precedent for innovative solutions in global carbon trade systems. Future research should explore the expansion of this model to other regions and investigate policy frameworks that facilitate its broader adoption, ensuring its long-term impact in combating climate change.

REFERENCES

[1] M. Gomez and C. Grady, "A balancing act: the interplay of food supply chain resilience and environmental

sustainability in American cities," *Environ. Res. Lett.*, vol. 18, no. 12, 2023, doi: 10.1088/1748-9326/ad0608.
[2] J. S. Marcus, "COVID-19 and the shift to remote work," *Beyond Pandemic? Explor. Impact COVID-19 Telecommun. Internet*, no. June 2022, pp. 71–102, 2023, doi: 10.1108/978-1-80262-049-820231003.
[3] D. Thi, V. Q. Tran, and D. T. Nguyen, "The relationship between renewable energy consumption, international tourism, trade openness, innovation and carbon dioxide emissions: international evidence," *… J. Sustain. Energy*, 2023, doi: 10.1080/14786451.2023.2192827.
[4] C. G. Azuero-Pedraza, P. Lauri, A. Lessa Derci Augustynczik, and V. M. Thomas, "Managing forests for biodiversity conservation and climate change mitigation," *Environ. Sci. Technol.*, vol. 58, no. 21, pp. 9175–9186, 2024.
[5] S. Gülsoy, M. G. Negiz, S. Özdemir, B. Yalçınkaya, and M. D. Ulusan, "Impacts of climate change on living organisms," *For. Agric. Stud. from Differ. Perspect.*, pp. 73–112, 2022.
[6] A. R. Mostafa, A. M. Owes, and S. Ghoniem, "Interconnected Impacts of Climate Change on Biodiversity, Agriculture, and Human Health," *Adv. Basic Appl. Sci.*, 2025.
[7] B. S. Probst *et al.*, "Systematic assessment of the achieved emission reductions of carbon crediting projects," *Nat. Commun.*, vol. 15, no. 1, p. 9562, 2024.
[8] H. Fiegenbaum, "Complementing Carbon Credits from Forest-Related Activities with Biodiversity Insurance and Resilience Value," *arXiv Prepr. arXiv2411.08452*, 2024.
[9] S. Dixit and S. Bardiya, "Carbon Trading in Developing Economies: Challenges, Opportunities, and Best Practices," *Int. J. Multidiscip. Res.*, vol. 6, Nov. 2024, doi: 10.36948/ijfmr.2024.v06i06.30282.
[10] S. Liu, W. Tang, and J. Zhang, "China's Carbon Emission Trading Mechanism: Realistic Challenges and Practical Pathways," *Highlights Business, Econ. Manag.*, vol. 43, pp. 87–91, Dec. 2024, doi: 10.54097/epvbhr86.
[11] L. Qiu, Z. Chang, X. Luo, S. Chen, J. Jiang, and L. Lei, "Monitoring Forest Disturbances and Associated Driving Forces in Guangdong Province Using Long-Term Landsat Time Series Images," *Forests*, vol. 16, no. 1, p. 189, 2025.
[12] S. Van Winckel, J. Simons, S. Lhermitte, and B. Muys, "Assessing the effect of forest management on above-ground carbon stock by remote sensing," *EGUsphere*, vol. 2025, pp. 1–22, 2025.
[13] B. Hosseiny, M. Zaboli, and S. Homayouni, "Forest Change Mapping using Multi-Source Satellite SAR, Optical, and LiDAR Remote Sensing Data," *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. 10, pp. 163–168, 2024.
[14] S. Illarionova, P. Tregubova, I. Shukhratov, D. Shadrin, A. Efimov, and E. Burnaev, "Advancing forest carbon stocks' mapping using a hierarchical approach with machine learning and satellite imagery," *Sci. Rep.*, vol. 14, no. 1, p. 21032, 2024.
[15] A. Nguyen and S. Saha, "Machine Learning and Multi-source Remote Sensing in Forest Carbon Stock Estimation: A Review," *arXiv Prepr. arXiv2411.17624*, 2024.
[16] E. C. Onukwulu, M. O. Agho, N. L. Eyo-Udo, A. K. Sule, and C. Azubuike, "Advances in blockchain integration for transparent renewable energy supply chains," *Int. J. Res. Innov. Appl. Sci.*, vol. 9, no. 12, pp. 688–714, 2024.
[17] S. Saraji and M. Borowczak, "A blockchain-based carbon credit ecosystem," *arXiv Prepr. arXiv2107.00185*, 2021.
[18] Y.-C. Tsai, "Enhancing Transparency and Fraud Detection in Carbon Credit Markets Through Blockchain-Based Visualization Techniques," *Electronics*, vol. 14, no. 1, p. 157, 2025.
[19] P. K. Patro, R. Jayaraman, A. Acquaye, K. Salah, and A. Musamih, "Blockchain-based solution to enhance carbon footprint traceability, accounting, and offsetting in the passenger aviation industry," *Int. J. Prod. Res.*, pp. 1–34, 2024.
[20] A. K. Jha, A. K. Jha, P. M. Pawar, and R. Muthalagu, "Design of a Carbon Offsetting and Trading Framework Using Blockchain and Internet of Things," *Available SSRN 5082355*, 2025.
[21] S. B. Prapulla *et al.*, "Blockchain-Powered Carbon Credit Management: Innovating Sustainability Tracking," in *2024 8th International Conference on Computational System and Information Technology for Sustainable Solutions (CSITSS)*, IEEE, 2024, pp. 1–7.
[22] J. Doblas *et al.*, "DETER-RT: The new INPE-TropiSCO deforestation monitoring system in the Amazon biome," *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. 48, pp. 127–133, 2024.
[23] C. G. Messias *et al.*, "DETER Monitoring on Non-Forest Vegetation in the Brazilian Amazon," *Rev. Bras. Cartogr.*, vol. 76, p. 2024, Oct. 2024, doi: 10.14393/rbcv76n0a-72531.
[24] I. R. McGregor, G. Connette, and J. M. Gray, "A multi-source change detection algorithm supporting user customization and near real-time deforestation detections," *Remote Sens. Environ.*, vol. 308, p. 114195, 2024.
[25] A. K. Maurya and A. Kumar, "The Role of GIS in the Study of Sustainable Development and Environmental Management," 2024.
[26] Z. Khafizova, U. Mukhtarov, and K. Nodira, "Study of using GIS technologies in forestry cadastre and monitoring for environmental sustainability," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2024, p. 12006.
[27] N. Hanafi, A. Jauhari, and G. M. Hatta, "Spatial Model of Carbon Stocks in Special Purpose Forest Area (KHDTK) Mungku Baru, Central Kalimantan Province, Indonesia," *J. Sylva Lestari*, vol. 13, no. 1, pp. 159–172, 2025.
[28] Z. Guo *et al.*, "Measuring above-ground carbon stock using spatial analysis and the InVEST model: application in the Thoria Watershed, India," *Environ. Res. Commun.*, vol. 6, no. 11, p. 115036, 2024.
[29] G. Shi *et al.*, "Spatiotemporal Pattern Analysis and Prediction of Carbon Storage Based on Land Use and Cover Change: A Case Study of Jiangsu Coastal Cities in China," *Land*, vol. 13, no. 11, p. 1728, 2024.