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DESIGNING AUDIT-DEFENSIBLE DIGITAL MRV FOR CARBON CONSERVATION: LESSONS FROM THE VMRV/VCARBON CASE IN INDONESIA

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Abstract

The increasing demand for transparency, accountability, and environmental integrity in carbon conservation has accelerated the transition from conventional Measurement, Reporting, and Verification (MRV) systems to digital MRV (Digital MRV). However, many existing digital platforms continue to face challenges related to data traceability, interoperability, audit readiness, and compliance with international carbon accounting standards. This study aims to develop an audit-defensible Digital MRV framework for carbon conservation by examining the implementation of the VMRV/VCARBON platform in Indonesia. A qualitative case study approach was employed using the Design Science Research (DSR) methodology to analyze the design principles of a reliable Digital MRV system. Data were collected through semi-structured interviews with carbon project stakeholders, Digital MRV developers, auditors, environmental experts, and policymakers, complemented by document analysis of technical reports, regulatory frameworks, IPCC guidelines, UNFCCC transparency requirements, and ISO 14064 standards. The data were analyzed using thematic analysis to identify key dimensions of an audit-defensible Digital MRV architecture. The findings indicate that the VMRV/VCARBON platform significantly enhances transparency, traceability, accountability, and data integrity by integrating remote sensing, cloud computing, artificial intelligence, standardized carbon accounting methodologies, digital audit trails, and registry management within a unified digital ecosystem. The study also identifies institutional interoperability, methodological standardization, human resource capacity, and cybersecurity as critical challenges for large-scale implementation. Based on these findings, the study proposes an audit-defensible Digital MRV framework consisting of six interconnected dimensions: digital data acquisition, automated carbon estimation, governance and regulatory compliance, digital auditing, registry integration, and decision-support systems. The proposed framework contributes to both theory and practice by providing a comprehensive model for developing transparent, scalable, and internationally credible Digital MRV systems that support carbon conservation, strengthen environmental integrity, and enhance Indonesia's participation in global voluntary carbon markets.

Keywords: *Digital MRV; Carbon Conservation; Audit-Defensible Framework; VMRV/VCARBON; Carbon Governance; Voluntary Carbon Market; Environmental Integrity.*

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Abstrak

Meningkatnya tuntutan terhadap transparansi, akuntabilitas, dan integritas lingkungan dalam konservasi karbon telah mendorong transformasi dari sistem Measurement, Reporting, and Verification (MRV) konvensional menuju Digital MRV. Namun, implementasi berbagai platform Digital MRV masih menghadapi tantangan terkait keterlacakan data (traceability), interoperabilitas, kesiapan audit, serta kesesuaian dengan standar internasional akuntansi karbon. Penelitian ini bertujuan untuk merancang kerangka Digital MRV yang audit-defensible dalam mendukung konservasi karbon melalui studi kasus implementasi platform VMRV/VCARBON di Indonesia. Penelitian menggunakan pendekatan studi kasus kualitatif dengan metode Design Science Research (DSR) untuk mengembangkan kerangka konseptual Digital MRV yang kredibel dan dapat dipertanggungjawabkan. Data diperoleh melalui wawancara semi-terstruktur dengan pengembang platform Digital MRV, pengelola proyek karbon, auditor, validator, pakar lingkungan, dan pembuat kebijakan, serta didukung oleh analisis dokumen yang meliputi laporan teknis, regulasi nasional, pedoman IPCC, kerangka transparansi UNFCCC, dan standar ISO 14064. Analisis data dilakukan menggunakan analisis tematik untuk mengidentifikasi dimensi utama dalam perancangan Digital MRV yang siap diaudit (audit-defensible). Hasil penelitian menunjukkan bahwa platform VMRV/VCARBON mampu meningkatkan transparansi, keterlacakan, akuntabilitas, dan integritas data melalui integrasi teknologi penginderaan jauh, komputasi awan, kecerdasan buatan, metodologi akuntansi karbon yang terstandarisasi, jejak audit digital (digital audit trail), serta sistem registri karbon dalam satu ekosistem digital yang terintegrasi. Penelitian ini juga mengidentifikasi bahwa interoperabilitas kelembagaan, standarisasi metodologi, kapasitas sumber daya manusia, dan keamanan siber merupakan tantangan utama dalam implementasi Digital MRV secara luas. Berdasarkan temuan tersebut, penelitian ini mengusulkan kerangka Audit-Defensible Digital MRV yang terdiri atas enam dimensi utama, yaitu akuisisi data digital, estimasi karbon otomatis, tata kelola dan kepatuhan regulasi, audit digital, integrasi registri karbon, serta sistem pendukung pengambilan keputusan. Kerangka yang dihasilkan memberikan kontribusi teoritis dan praktis sebagai model Digital MRV yang transparan, skalabel, dan memenuhi standar internasional untuk mendukung konservasi karbon, memperkuat integritas lingkungan, serta meningkatkan daya saing Indonesia dalam pasar karbon sukarela global.

Kata Kunci: Digital MRV; Konservasi Karbon; Audit-Defensible; VMRV/VCARBON; Tata Kelola Karbon; Pasar Karbon Sukarela; Integritas Lingkungan.

1. Introduction

Climate change has accelerated the transformation of carbon governance from conventional administrative approaches toward data-driven digital systems capable of generating timely, accurate, and verifiable information. In this context, Measurement, Reporting, and Verification (MRV) serves as the fundamental framework for ensuring that every claim of greenhouse gas (GHG) emission reduction or carbon sequestration is scientifically credible. As global carbon markets continue to expand and transparency requirements become increasingly stringent, conventional MRV systems face significant limitations, including high verification costs, delayed reporting, inconsistent datasets, and limited interoperability across platforms. Consequently, the transition toward digital MRV (dMRV) has emerged as a strategic solution to enhance the credibility, efficiency, and scalability of carbon governance while supporting the growing complexity of carbon trading mechanisms (IPCC, 2022; UNFCCC, 2021; Körner et al., 2025).

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Indonesia occupies a strategically important position in global carbon conservation due to its vast tropical forests, peatlands, and mangrove ecosystems, which collectively represent some of the world's largest natural carbon reservoirs. These ecosystems provide substantial opportunities for developing high-quality carbon conservation projects capable of contributing to international climate mitigation efforts. However, realizing this potential requires an MRV system that produces transparent, consistent, and internationally accepted carbon accounting data. Without a robust verification framework, the environmental integrity and market value of Indonesian carbon credits may be undermined by reduced confidence among investors, certification bodies, and international stakeholders (Arifanti et al., 2022; IPCC, 2022).

Recent technological advances have fundamentally reshaped MRV practices through the integration of remote sensing, Internet of Things (IoT), artificial intelligence (AI), cloud computing, blockchain technology, and machine learning-based spatial analytics. These technologies enable continuous monitoring of carbon stocks, automate data processing, and improve the accuracy of carbon estimation while significantly reducing operational costs. Moreover, digital technologies facilitate near-real-time monitoring and establish transparent data management processes that strengthen accountability throughout the carbon accounting lifecycle (Körner et al., 2025; Luo et al., 2024).

Nevertheless, the effectiveness of digital MRV extends beyond technological sophistication. Its success largely depends on the ability to generate digital evidence that withstands rigorous independent auditing. The concept of an audit-defensible digital MRV emphasizes that every stage of data acquisition, processing, storage, analysis, and reporting must be supported by comprehensive audit trails, immutable records, and transparent documentation. Such characteristics ensure that carbon accounting results remain traceable, reproducible, and resistant to manipulation, thereby strengthening the integrity of carbon conservation projects and enhancing stakeholder trust (Körner et al., 2025; Ding & Lu, 2026).

The rapid expansion of the Voluntary Carbon Market (VCM) has further increased the demand for digital systems capable of ensuring the environmental integrity of carbon credits. Numerous international assessments have identified methodological weaknesses, inaccurate baselines, limited transparency, and insufficient verification procedures as major contributors to declining public confidence in voluntary carbon offsets. These challenges highlight the necessity of digital MRV systems that effectively minimize risks associated with double counting, data manipulation, and discrepancies between reported and actual field conditions (West et al., 2023; Körner et al., 2025).

In response to these challenges, Indonesia has begun developing integrated digital platforms such as VMRV/VCARBON, designed to support carbon conservation through digital measurement, reporting, and verification. The platform integrates spatial information, carbon inventory databases, digital reporting tools, and verification workflows into a unified ecosystem that connects project developers, government agencies, verification bodies, and carbon credit buyers. Such integration has the potential to improve certification efficiency while increasing transparency, accountability, and

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confidence in Indonesia's carbon governance framework (UNFCCC, 2021; Körner et al., 2025).

A key advantage of digital MRV lies in its capacity to integrate heterogeneous data sources into a coherent and interoperable information system. Satellite imagery, field inventory data, environmental sensors, conservation activity records, and metadata can be automatically synthesized to generate reliable carbon stock estimates along with quantified uncertainty assessments. This integrated approach not only enhances consistency and reproducibility but also fulfills the transparency requirements established by internationally recognized carbon accounting and auditing standards (Wadoux et al., 2026; Anderson et al., 2026).

Beyond technological innovation, successful implementation of digital MRV requires an adaptive governance framework that addresses institutional, regulatory, and organizational dimensions. Standardized methodologies, interoperability protocols, cybersecurity mechanisms, data ownership policies, and alignment with national regulations are essential for ensuring the long-term sustainability of digital carbon governance systems. Without adequate institutional support, digital transformation may merely automate existing processes without substantially improving governance quality or environmental integrity. Therefore, audit-defensible digital MRV should be viewed as an integrated combination of technological innovation, regulatory compliance, and institutional capacity building (UNFCCC, 2021; Wijaya et al., 2021).

The VMRV/VCARBON initiative provides a valuable empirical case for understanding how digital MRV systems can be designed to satisfy the rigorous requirements of modern carbon auditing. Lessons derived from its implementation contribute to the development of a conceptual framework for audit-defensible digital MRV that emphasizes transparency, traceability, accountability, data integrity, and compliance with internationally recognized standards. These principles are increasingly regarded as prerequisites for enhancing the credibility and market acceptance of carbon conservation projects in Indonesia and beyond (Körner et al., 2025; Ding & Lu, 2026).

Based on these considerations, this study entitled "Designing Audit-Defensible Digital MRV for Carbon Conservation: Lessons from the VMRV/VCARBON Case in Indonesia" aims to examine the fundamental principles underlying the design of a robust digital MRV system capable of supporting credible carbon conservation initiatives. The study seeks to develop conceptual and practical recommendations for designing digital MRV architectures that meet international auditing requirements, strengthen confidence in Indonesian carbon credits, and reinforce Indonesia's contribution to global climate change mitigation through transparent, accountable, and evidence-based carbon governance (IPCC, 2022; Körner et al., 2025; UNFCCC, 2021).

2. Research Method

This study employed a qualitative case study approach to investigate the design of an audit-defensible Digital Measurement, Reporting, and Verification (Digital MRV) system for carbon conservation through the implementation of the VMRV/VCARBON platform in Indonesia. A qualitative case study was selected because it enables an in-depth

exploration of complex socio-technical phenomena within their real-world context, particularly where technological innovation, institutional governance, and environmental accountability intersect (Yin, 2018). The VMRV/VCARBON platform was chosen as the case because it represents one of Indonesia's emerging digital initiatives for integrating carbon measurement, reporting, verification, and registry management into a unified ecosystem that supports carbon conservation and voluntary carbon markets. The research was guided by the Design Science Research (DSR) methodology, which aims to develop and evaluate innovative artifacts capable of addressing practical organizational problems (Peffers et al., 2007). In this study, the proposed artifact is a conceptual framework for an audit-defensible Digital MRV system that integrates digital technologies, governance mechanisms, and internationally recognized auditing principles. The research process consisted of six stages: (1) identifying challenges associated with conventional MRV systems, (2) defining design objectives for an audit-defensible Digital MRV architecture, (3) designing the proposed framework based on empirical findings from the VMRV/VCARBON case, (4) demonstrating its applicability through case analysis, (5) evaluating the framework using internationally accepted carbon governance criteria, and (6) communicating theoretical and practical implications for digital carbon governance.

The collected data were analyzed using thematic analysis, following the six-step framework proposed by Braun and Clarke (2021). Initially, all interview transcripts and documentary evidence were thoroughly reviewed to gain familiarity with the dataset. Subsequently, meaningful codes were generated and systematically organized into broader themes representing critical dimensions of Digital MRV implementation. The analysis focused on identifying recurring patterns related to digital infrastructure, carbon accounting processes, audit trail mechanisms, data integrity, interoperability, governance structures, transparency, traceability, and verification practices. These themes served as the analytical foundation for constructing the proposed audit-defensible Digital MRV framework. To ensure the robustness of the proposed framework, its design was evaluated against internationally recognized principles of carbon accounting and climate transparency. The evaluation criteria were derived from the IPCC Guidelines for National Greenhouse Gas Inventories, the UNFCCC Enhanced Transparency Framework, ISO 14064, and internationally accepted principles developed by the Integrity Council for the Voluntary Carbon Market (ICVCM) and the Voluntary Carbon Markets Integrity Initiative (VCMI). The framework was assessed across six principal dimensions, namely transparency, traceability, data integrity, interoperability, scalability, and auditability. These dimensions were selected because they represent the essential characteristics of a credible Digital MRV system capable of supporting reliable carbon conservation projects and meeting international verification standards.

The credibility and trustworthiness of the research findings were strengthened through several validation strategies. Data triangulation was achieved by integrating information from interviews, technical documentation, regulatory frameworks, and scientific literature. Methodological triangulation was employed by combining qualitative interviews with documentary analysis to provide complementary perspectives on the research problem. Member checking was conducted by sharing preliminary interpretations with selected participants to verify the accuracy of the findings, while peer debriefing with experts in digital governance, environmental management, and carbon accounting helped improve analytical consistency and reduce researcher bias. These procedures contribute to the credibility, dependability, confirmability, and transferability of qualitative research findings (Lincoln & Guba, 1985). Finally, ethical considerations were maintained

throughout the research process. Participation in interviews was entirely voluntary, and informed consent was obtained from all participants before data collection commenced. Respondents' identities and organizational information were treated confidentially, and all collected data were securely stored and used exclusively for academic purposes. Any sensitive information related to the VMRV/VCARBON platform or participating organizations was anonymized to ensure compliance with research ethics while preserving the scientific integrity and transparency of the study.

3. Results and Discussion

3.1 Designing an Audit-Defensible Digital MRV Architecture

The findings reveal that the VMRV/VCARBON platform represents a significant shift from conventional carbon monitoring systems toward a comprehensive digital ecosystem capable of supporting transparent, accountable, and audit-ready carbon governance. Unlike traditional Measurement, Reporting, and Verification (MRV) systems, which frequently depend on manual documentation, fragmented databases, and paper-based verification processes, VMRV/VCARBON integrates data acquisition, carbon estimation, reporting, verification, and registry management into a single digital platform. This integration minimizes data duplication, enhances consistency across project activities, and significantly reduces administrative complexity throughout the carbon accounting cycle. The findings are consistent with Körner et al. (2025), who argue that digital MRV enhances governance quality by integrating digital technologies into every stage of carbon accounting.

The architectural analysis indicates that the platform is composed of several interconnected functional layers that collectively support audit-defensible carbon conservation. Carbon-related information is first collected through multiple digital sources, including satellite imagery, unmanned aerial vehicle (UAV) observations, field inventory measurements, Global Positioning System (GPS) data, environmental sensors, and historical land-cover datasets. These heterogeneous datasets are subsequently integrated within a centralized cloud-based environment where automated processing algorithms estimate carbon stocks and greenhouse gas removals using standardized methodologies consistent with IPCC guidelines. The processed information is then converted into standardized digital reports that comply with national and international carbon accounting requirements before undergoing independent verification through secure digital interfaces. Finally, verified carbon credits are registered within an integrated registry system that records every transaction through immutable digital documentation, thereby reducing opportunities for duplicate claims and enhancing overall market credibility (IPCC, 2022; Luo et al., 2024).

The findings suggest that digital integration fundamentally changes the role of MRV from a purely technical reporting mechanism into a comprehensive governance infrastructure. Rather than serving only as a tool for documenting carbon inventories, Digital MRV functions as an integrated information system capable of connecting project developers, verification bodies, government institutions, carbon registries, and market participants within a transparent digital environment. Such integration improves not only operational efficiency but also institutional trust, which has become a critical requirement in rapidly expanding voluntary carbon markets.

3.2 Transparency and Traceability as Foundations of Audit Readiness

A major finding emerging from the VMRV/VCARBON case concerns the substantial improvement in transparency and data traceability achieved through digitalization. The platform automatically records every activity performed throughout the carbon accounting process, including data collection, processing, revision, verification, approval, and registry issuance. Each transaction generates digital metadata containing timestamps, user identification, processing history, methodological references, and supporting documentation, thereby creating a complete audit trail that can be reconstructed at any stage of project implementation.

Compared with conventional MRV systems, where historical documentation is often incomplete or dispersed across multiple institutions, the digital platform enables independent auditors to trace every reported carbon value back to its original source. This capability significantly strengthens confidence in carbon estimates because every modification is documented and supported by verifiable digital evidence. Consequently, transparency becomes embedded within the system architecture rather than depending solely on administrative compliance. Similar conclusions have been presented by the UNFCCC (2021), which identifies transparency and traceability as essential principles of climate governance under the Enhanced Transparency Framework.

The platform also facilitates interoperability among stakeholders by standardizing data structures and reporting formats. Carbon project developers, government agencies, independent validators, certification bodies, and carbon registry operators are able to access synchronized information using standardized digital protocols. This interoperability reduces inconsistencies among institutions and accelerates the verification process while maintaining data integrity throughout the carbon credit lifecycle.

3.3 Digital Auditability and the Integrity of Carbon Credits

One of the most important findings concerns the relationship between digital auditability and the environmental integrity of carbon credits. The study demonstrates that an audit-defensible Digital MRV system is characterized not merely by its ability to produce digital reports but by its capacity to preserve complete, verifiable, and immutable evidence throughout every stage of carbon accounting. Within the VMRV/VCARBON platform, auditors can examine original field observations, satellite imagery, biomass estimation models, processing algorithms, revision histories, supporting documents, and verification records through a unified digital interface.

The implementation of automated logging significantly reduces the possibility of undocumented data modification because every change generates permanent digital records. Furthermore, role-based access control ensures that only authorized personnel can modify datasets while maintaining comprehensive activity histories for auditing purposes. Version control mechanisms preserve previous records whenever updates occur, allowing auditors to compare historical and revised datasets without losing original information. These characteristics substantially improve accountability and reduce opportunities for intentional or unintentional manipulation of carbon estimates.

The findings indicate that digital auditability directly contributes to increasing the credibility of carbon credits within voluntary carbon markets. Investors and certification bodies require confidence that reported emission reductions are supported by transparent methodologies and independently verifiable evidence. Consequently, Digital MRV should not be viewed solely as an operational information system but rather as an institutional

mechanism for strengthening environmental integrity and market confidence. This observation supports Ding and Lu (2026), who emphasize that blockchain-enabled Digital MRV systems enhance trust by maintaining immutable records and strengthening audit transparency.

3.4 Institutional and Governance Challenges

Despite the considerable advantages of Digital MRV implementation, the study identifies several institutional challenges that continue to constrain its effectiveness in Indonesia. One of the primary challenges concerns interoperability among governmental institutions responsible for forestry, environmental protection, land administration, and climate policy. These institutions frequently maintain independent databases using different metadata standards, spatial resolutions, and reporting procedures, creating barriers to seamless information exchange. Without harmonized national data standards, interoperability remains limited despite technological advances.

Another challenge relates to methodological standardization. Carbon conservation projects implemented by different organizations often employ varying biomass equations, sampling designs, monitoring frequencies, and uncertainty assessment methods. Such methodological diversity complicates the comparison and aggregation of carbon accounting results across projects. The findings therefore emphasize the importance of establishing nationally standardized Digital MRV protocols that are fully aligned with IPCC guidelines and international verification requirements.

Human resource capacity also emerged as an important determinant of successful Digital MRV implementation. Effective operation of integrated digital platforms requires multidisciplinary expertise encompassing remote sensing, geographic information systems, artificial intelligence, environmental science, carbon accounting, digital auditing, and information technology. Interviews indicate that many implementing organizations continue to experience shortages of professionals possessing these interdisciplinary competencies. Consequently, long-term investments in institutional capacity building remain essential for supporting national Digital MRV implementation.

Cybersecurity represents an additional governance concern. As carbon accounting increasingly depends on cloud computing, online databases, and interconnected digital infrastructures, protecting sensitive environmental information against unauthorized access becomes increasingly important. Strong cybersecurity mechanisms are therefore necessary not only for protecting data confidentiality but also for maintaining stakeholder trust in digital carbon governance systems.

3.5 Proposed Audit-Defensible Digital MRV Framework

Drawing upon the empirical findings, this study proposes a conceptual framework for designing an audit-defensible Digital MRV system that integrates technological innovation with governance principles. The framework consists of six interconnected dimensions. The first dimension involves digital data acquisition through satellite imagery, UAV observations, Internet of Things (IoT) sensors, GPS measurements, and field inventories. The second dimension focuses on automated data integration and carbon estimation using artificial intelligence, cloud computing, spatial analytics, and standardized carbon accounting methodologies. The third dimension addresses governance and regulatory compliance by incorporating national carbon regulations, IPCC

guidelines, ISO 14064 standards, and institutional operating procedures into system design.

The fourth dimension emphasizes digital auditing through comprehensive audit trails, version control mechanisms, independent verification interfaces, immutable documentation, and transparent evidence repositories. The fifth dimension integrates Digital MRV with national and international carbon registries to facilitate carbon credit issuance while preventing duplicate registrations and improving interoperability among market participants. Finally, the sixth dimension provides decision-support capabilities through interactive dashboards, performance indicators, risk monitoring, predictive analytics, and policy evaluation tools that assist decision-makers in managing carbon conservation projects more effectively.

The proposed framework demonstrates that technological innovation alone cannot guarantee credible carbon governance. Rather, audit-defensible Digital MRV requires balanced integration among digital infrastructure, institutional governance, internationally recognized standards, transparent auditing procedures, and organizational capacity. Such integration transforms Digital MRV into a comprehensive governance framework capable of supporting reliable carbon conservation initiatives at national and international levels.

5.6 Implications for Carbon Governance and Sustainable Carbon Markets

The findings have important implications for future carbon governance in Indonesia and other developing countries seeking to strengthen climate transparency. First, Digital MRV should be recognized as a strategic governance instrument rather than merely a technological innovation. Its greatest contribution lies in strengthening transparency, accountability, traceability, and environmental integrity across the entire carbon credit lifecycle. These characteristics are increasingly required by international certification standards and voluntary carbon markets seeking high-quality carbon credits.

Second, successful Digital MRV implementation requires institutional harmonization among government agencies, project developers, certification bodies, and registry operators. Interoperable information systems supported by standardized methodologies will substantially improve verification efficiency while reducing transaction costs. Third, integrating emerging digital technologies including artificial intelligence, remote sensing, blockchain, cloud computing, and advanced spatial analytics creates significant opportunities for developing scalable, evidence-based carbon governance systems capable of supporting national climate commitments under the Paris Agreement.

Overall, the VMRV/VCARBON case demonstrates that designing an audit-defensible Digital MRV system requires simultaneous attention to technological capability, institutional governance, regulatory compliance, methodological consistency, and digital transparency. The integration of these components establishes a robust foundation for enhancing the credibility of Indonesian carbon conservation projects, increasing confidence among international investors, and strengthening Indonesia's contribution to global climate change mitigation through transparent, accountable, and scientifically defensible carbon governance.

5. Conclusion

This study demonstrates that the development of an audit-defensible Digital Measurement, Reporting, and Verification (Digital MRV) system represents a fundamental advancement in carbon conservation governance by integrating digital technologies with internationally recognized auditing principles. Evidence from the VMRV/VCARBON case in Indonesia indicates that Digital MRV extends beyond conventional carbon accounting functions, evolving into a comprehensive governance framework that enhances transparency, traceability, accountability, and data integrity throughout the carbon project lifecycle. The integration of geospatial technologies, remote sensing, cloud computing, artificial intelligence, standardized reporting, and digital verification establishes a robust ecosystem capable of producing credible and auditable carbon information that satisfies both national regulatory requirements and international carbon market standards.

The findings further reveal that the effectiveness of an audit-defensible Digital MRV system depends not only on technological innovation but also on the integration of institutional governance, standardized methodologies, interoperable information systems, and rigorous verification mechanisms. Comprehensive digital audit trails, immutable documentation, standardized workflows, and secure data management significantly strengthen confidence in carbon accounting results while reducing risks associated with data inconsistency, manipulation, and double counting. Consequently, Digital MRV enhances the environmental integrity of carbon credits and increases stakeholder confidence in voluntary carbon market transactions.

Despite these advances, several institutional challenges remain, including limited interoperability among governmental databases, methodological inconsistencies across carbon projects, shortages of multidisciplinary human resources, and increasing cybersecurity requirements. Addressing these challenges requires harmonized national standards, strengthened institutional collaboration, continuous capacity building, and strategic investment in digital infrastructure. Therefore, successful implementation of Digital MRV should be regarded as a socio-technical transformation that combines technological innovation with organizational readiness and effective governance.

Based on the empirical evidence obtained from the VMRV/VCARBON case, this study proposes an audit-defensible Digital MRV framework that integrates six essential dimensions: digital data acquisition, automated carbon estimation, governance and regulatory compliance, digital auditing, registry integration, and decision-support systems. These interconnected components provide a conceptual foundation for developing transparent, scalable, and internationally credible carbon conservation systems capable of supporting Indonesia's Nationally Determined Contributions (NDCs) under the Paris Agreement while strengthening participation in global voluntary carbon markets.

Finally, this study contributes to both theory and practice by extending the conceptual understanding of Digital MRV from a technical monitoring instrument to an integrated digital governance framework for carbon conservation. The proposed framework offers practical guidance for policymakers, carbon project developers, verification bodies, and digital platform designers seeking to establish reliable, transparent, and audit-ready carbon accounting systems. Future research may further validate and refine the proposed framework through comparative studies across different Digital MRV platforms, integration of blockchain-based carbon registries, and quantitative

evaluation of Digital MRV performance under diverse ecological and institutional contexts.

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