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INTEGRATION OF DIGITAL CARBON TRADING SYSTEMS WITH CIRCULAR ECONOMY PRINCIPLES: A COMPREHENSIVE REVIEW OF SUCCESSFUL IMPLEMENTATION APPROACHES

Sylviana Maya Damayanti[1], Arinda Mentari Putri[2], Aghnia Nadhira Aliya Putri[3*], Rozan Hanifan[4], Sulastri[5], Ratih Hurriyati[6], IrwanTrinugroho[7]

[1]School of Business and Management, Institut Teknologi Bandung (ITB), Bandung, West Java, Indonesia. Email: sylvianamaya@itb.ac.id. Orcid ID: https://orcid.org/0000-0002-1717-8505
[2]School of Business and Management, Institut Teknologi Bandung (ITB), Bandung, West Java, Indonesia. Email: arinda.mp@sbm-itb.ac.id. Orcid ID: https://orcid.org/0009-0008-5743-579X
[3]School of Business and Management, Institut Teknologi Bandung (ITB), Bandung, West Java, Indonesia. Email: aghnia_nadhira@sbm-itb.ac.id, Orcid ID: https://orcid.org/0000-0003-4429-9772
[4]School of Business and Management, Institut Teknologi Bandung (ITB), Bandung, West Java, Indonesia. Email: rozan_hanifan@sbm-itb.ac.id Orcid ID: https://orcid.org/0000-0001-5207-5176
[5]Faculty of Economics and Business Education, Universitas Pendidikan Indonesia, Bandung, West Java, Indonesia. Email: sulastri@upi.edu. Orcid ID: https://orcid.org/0000-0001-6091-4451
[6]Faculty of Economics and Business Education, Universitas Pendidikan Indonesia, Bandung, West Java, Indonesia. Email: ratih@upi.edu. Orcid ID: https://orcid.org/0000-0002-7792-360X
[7]Faculty of Economics and Business, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia. Email: irwan_t@staff.uns.ac.id. Orcid ID: https://orcid.org/0000-0003-4911-7982

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Corresponding Author: Aghnia Nadhira Aliya Putri (aghnia_nadhira@sbm-itb.ac.id)

ABSTRACT

The urgent global commitment to reach carbon neutrality by 2050 has catalyzed advancements in carbon management technologies, however, meaningful stakeholder engagement in digitalized carbon trading platforms continues to face barriers including insufficient technological competence, policy ambiguities, and inadequate incorporation of circular economy principles. This comprehensive literature analysis investigates successful engagement approaches in digital carbon trading systems through the lens of circular economy implementation, evaluating technological facilitators and stakeholder involvement frameworks across various organizational levels. Adhering to PRISMA methodology, 227 initial Scopus database entries were systematically filtered to 86 rigorous studies spanning 2006-2025 utilizing the Theory of Change analytical framework. Findings demonstrate exponential scholarly expansion from 5 publications in 2021 to 25 in 2024, with China at the forefront contributing 23 studies while manufacturing industries predominate with 31 investigations. Advanced digital solutions encompassing artificial intelligence, Internet of Things, distributed ledger technology, and virtual modeling systems facilitate automated validation and continuous monitoring, although technological competency deficits limit broad-scale implementation. Circular economy

implementations show remarkable promise through energy recovery systems achieving annual reductions of 77,826 tons CO_2 equivalent, resource reclamation generating 8.27 million tons CO_2 equivalent benefits, and organic waste processing offering $64,000-$154,000 net present value opportunities. Stakeholder engagement exhibits considerable variation, with small-to-medium enterprises encountering technological obstacles while large corporations showcase sophisticated closed-circuit applications. The investigation demonstrates convergence with numerous Sustainable Development Goal objectives, highlighting requirements for comprehensive frameworks that address technological expandability, financial feasibility, social equity, and regulatory alignment to unlock digital carbon markets' capacity as catalysts for sustainable progress and circular economy transition.

KEYWORDS: Digital Carbon Markets, Circular Economy, Stakeholder Participation, Blockchain Technology, Carbon Trading, Sustainability.

1. INTRODUCTION

The global imperative to achieve net-zero emissions by 2050 has catalyzed unprecedented innovation in carbon management systems and sustainable business models. As countries worldwide grapple with the dual challenges of economic growth and environmental stewardship, the integration of digital technologies with carbon trading mechanisms has emerged as a critical pathway toward decarbonization (Ayres et al., 2025; Olawade et al., 2025). The Paris Agreement's ambitious targets, coupled with mounting pressure from stakeholders and regulatory bodies, have created an urgent need for sophisticated, scalable solutions that can effectively measure, trade, and offset carbon emissions across diverse industries and geographies. This transformation is particularly evident in the rapid evolution from traditional linear economic models to circular economy frameworks that prioritize resource efficiency, waste minimization, and regenerative practices.

Digital carbon markets represent a paradigmatic shift in how carbon credits are created, verified, and traded, leveraging blockchain technology, artificial intelligence, and Internet of Things (IoT) systems to enhance transparency, traceability, and efficiency (Alshammari et al., 2025; D'Adamo et al., 2023). These platforms facilitate automated carbon accounting, smart contract-based trading mechanisms, and real-time monitoring of emission reduction projects, thereby addressing longstanding issues of double counting, additionality verification, and market fragmentation that have historically plagued voluntary carbon markets. The integration of advanced digital technologies enables granular tracking of carbon flows throughout supply chains, from production and consumption to end-of-life management, creating unprecedented opportunities for precise carbon footprint quantification and offset generation (Zhou et al., 2022; Xia et al., 2020).

The convergence of circular economy principles with digital carbon markets has created synergistic opportunities for sustainable value creation, where waste-to-energy projects, material recovery initiatives, and nature-based solutions generate tradeable carbon credits while simultaneously advancing resource circularity (Cao et al., 2024; Pradhan & Meena, 2023). This integration manifests across multiple dimensions: waste reduction strategies that simultaneously minimize carbon emissions and create economic value, remanufacturing processes that extend product lifecycles while reducing embodied carbon, and regenerative practices that sequester atmospheric CO_2 while producing marketable environmental credits (Xu et al., 2021; Fernández-Ríos et al., 2023). The circular economy framework provides a robust foundation for carbon market participation by transforming traditional waste streams into revenue-generating carbon offset projects, thereby aligning environmental stewardship with economic incentives.

Despite the significant potential of digital carbon markets within circular economy frameworks, effective stakeholder participation remains constrained by multiple barriers including technological literacy gaps, regulatory uncertainties, high transaction costs, and limited access to verified offset projects (Singh Kharayat & Gupta, 2025; Wang et al., 2024). Small and medium enterprises, in particular, face substantial challenges in navigating complex carbon accounting methodologies, understanding blockchain-based trading platforms, and integrating carbon considerations into their circular business models (Tsai et al., 2023; Cheng et al., 2025). These participation barriers are further compounded by inconsistent policy frameworks, varying carbon pricing mechanisms across jurisdictions, and insufficient standardization of measurement, reporting, and verification (MRV) protocols, which collectively impede the development of liquid, transparent carbon markets that can effectively drive decarbonization at scale.

While existing literature has extensively explored carbon trading mechanisms and circular economy principles as separate domains, there remains a significant knowledge gap regarding the systematic integration of these approaches to enhance stakeholder participation in digital carbon markets (Barrett et al., 2013; Gupta & Palsule-Desai, 2011). Current research lacks comprehensive frameworks that address the multifaceted literacy requirements—encompassing technical, financial, and sustainability competencies—necessary for effective participation in digitalized carbon markets within circular economy contexts. Therefore, this systematic literature review aims to identify, analyze, and synthesize existing knowledge on effective participation strategies in digital carbon markets through circular economy applications, with particular emphasis on examining technological enablers, policy frameworks, and stakeholder engagement mechanisms that facilitate successful carbon market participation across different organizational scales and industrial sectors.

2. THEORITICAL BACKGROUND

To address this complexity, this study employs the Theory of Change (ToC) as a theoretical foundation to understand how various interventions and strategies can systematically enhance stakeholder participation in digital carbon markets. The Theory of Change provides a comprehensive framework for mapping the causal pathways from initial inputs (such as digital literacy programs, policy frameworks, and technological infrastructure) through intermediate outcomes (including enhanced stakeholder capabilities, regulatory clarity, and platform accessibility) to ultimate impacts (effective decarbonization and circular economy advancement). This theory is particularly relevant for understanding multi-stakeholder participation because it explicitly acknowledges the interconnected nature of change processes, allowing for the identification of critical assumptions, potential barriers, and necessary conditions that must be met for successful carbon market engagement across different organizational scales and sectoral contexts.

The application of Theory of Change in this context enables a systematic analysis of how circular economy principles can serve as catalysts for carbon market participation by creating multiple value streams—environmental, economic, and social—that motivate stakeholder engagement (Vandana & Cerchione, 2025; Poolsawad et al., 2023). By mapping the logical sequence from foundational literacy development (technical understanding of blockchain-based carbon platforms, financial comprehension of carbon pricing mechanisms, and sustainability knowledge of circular economy applications) to intermediate capacity building (platform navigation skills, investment decision-making capabilities, and circular business model integration) and finally to sustained market participation (regular carbon trading activities, development of carbon offset projects, and ecosystem leadership), the ToC framework helps identify where interventions are most needed and most likely to be effective. Therefore, this systematic literature review aims to identify, analyze, and synthesize existing knowledge on effective participation strategies in digital carbon markets through circular economy applications, with particular emphasis on examining how different theoretical and practical approaches align with or challenge the Theory of Change pathways for stakeholder engagement in carbon market ecosystems.

3. METHODOLOGY

This study employed a systematic literature review methodology to comprehensively examine effective participation strategies in digital carbon markets through circular economy integration. Systematic literature review represents a rigorous and transparent approach for synthesizing existing knowledge across fragmented research domains, particularly valuable when investigating emerging interdisciplinary fields where theoretical frameworks and empirical evidence require systematic consolidation (Awan et al., 2022; Rocha et al., 2024). Given the nascent nature of digital carbon markets and their integration with circular economy principles, this methodology was particularly suited to identify knowledge gaps, synthesize diverse theoretical perspectives, and establish a robust foundation for understanding stakeholder participation strategies. The systematic review process was conducted following established PRISMA guidelines (Maciuiene et al., 2024) to ensure methodological rigor and transparency throughout the research process.

As illustrated in Figure 1, the systematic review process was structured into three distinct phases following the PRISMA framework. The initial identification stage involved a comprehensive database search through Scopus using carefully constructed search terms that combined digital carbon market concepts with circular economy terminology. The search strategy employed Boolean operators to capture articles containing combinations of "digital carbon market," "carbon trading," "carbon credit," or "emission trading" alongside circular economy-related terms including "circular economy," "closed loop," "sustainable economy," or "resource efficiency," further refined by sustainability indicators such as "sustainability," "environmental impact," "green economy," or "eco-friendly." This comprehensive search strategy yielded an initial corpus of 227 records for systematic evaluation. The subsequent screening phase involved multiple filtering criteria based on subject area alignment with "Business, Management and Accounting" disciplines (excluding 77 records), publication type focusing on peer-reviewed articles only (excluding 20 non-article publications), and publication stage retaining final published articles (excluding 38 in-progress studies), with 4 additional documents discarded as irrelevant after full-text review.

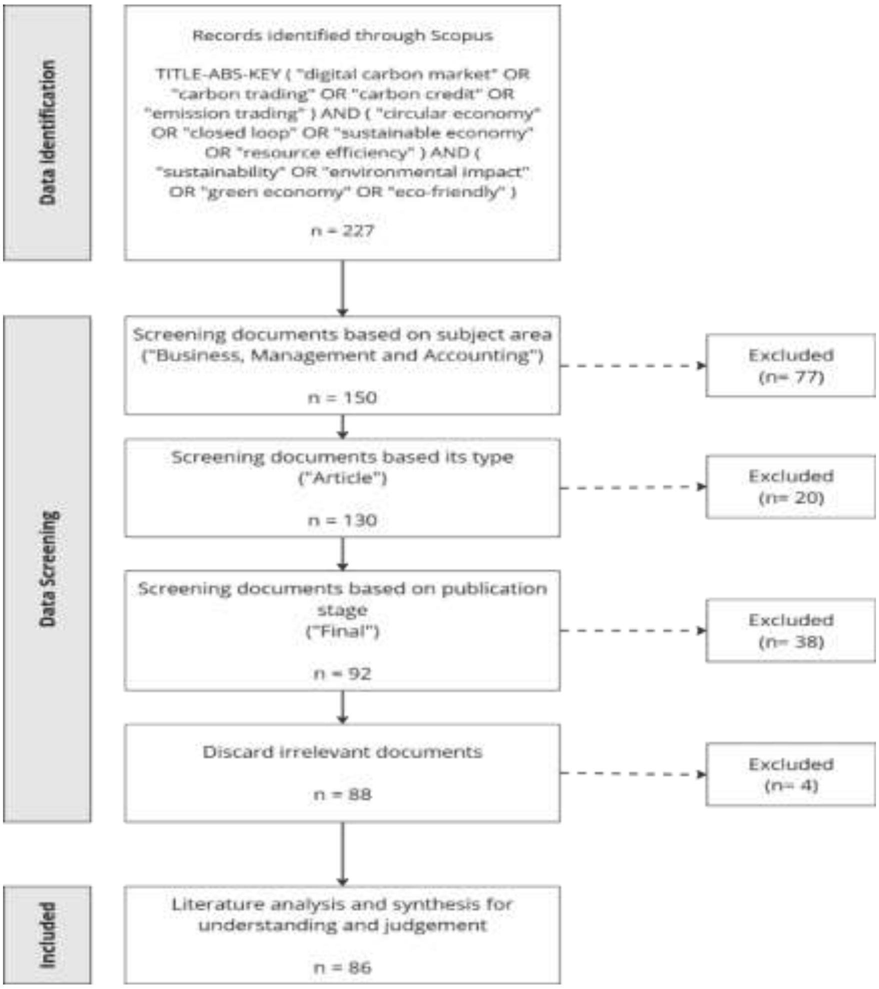

Figure 1: PRISMA Flow Diagram.

The final inclusion phase resulted in 86 high-quality studies that demonstrated clear empirical or theoretical contributions to understanding stakeholder participation strategies in digital carbon markets within circular economy contexts. Data extraction from the final corpus employed a structured coding framework that systematically captured key variables including geographical focus, research methodologies, theoretical frameworks, stakeholder categories, participation barriers, enabling technologies, policy mechanisms, and circular economy applications. Thematic analysis was subsequently conducted to identify recurring patterns, emerging themes, and theoretical connections across the literature, enabling the synthesis of comprehensive insights regarding effective participation strategies and their underlying mechanisms within the Theory of Change framework that guides this investigation.

Each included study was evaluated using a standardized rubric assessing five dimensions: methodological rigor, data quality and transparency, theoretical contribution, practical applicability, and publication quality (Table 1). Each criterion was scored 0-2 (not met, partially met, fully met), with a minimum threshold of 12/20 (60%) required for inclusion. Two independent reviewers conducted assessments, with disagreements resolved through discussion.

Table 1: Quality Assessment Rubric.

Assessment Dimension	Criteria	Scoring
Methodological Rigor	Clear research design and methodology	0-2
	Appropriate data collection methods	0-2
Data Quality & Transparency	Data sources clearly identified	0-2
	Sample size/scope adequate for conclusions	0-2
Theoretical Contribution	Theoretical framework clearly articulated	0-2
	Contribution to knowledge explicitly stated	0-2
Practical Applicability	Stakeholder implications discussed	0-2

	Implementation feasibility considered	0-2
5. Publication Quality	Published in peer-reviewed journal	0-2
	Citation impact (for studies >2 years old)	0-2
Minimum Threshold for Inclusion	Total Score: 12/20 (60%)	Maximum Score: 20

4. RESULTS

4.1. Research Publication Trends and Temporal Evolution

The analysis of publication trends reveals a dynamic evolution in research interest regarding digital carbon markets and circular economy integration over the past two decades. As illustrated in Figure 2, the research trajectory demonstrates three distinct phases of development that align with major global climate policy milestones and technological advancement cycles. The foundational period (2006-2013) averaged less than one publication per year, reflecting early explorations of basic carbon trading mechanisms following the Kyoto Protocol implementation. During this phase, researchers like Fröhling et al. (2009) established initial frameworks for emission trading in industrial contexts, while Drury (2010) examined resource efficiency strategies that would later inform circular economy applications. These foundational studies primarily focused on traditional carbon market structures and preliminary sustainability concepts without significant technological integration.

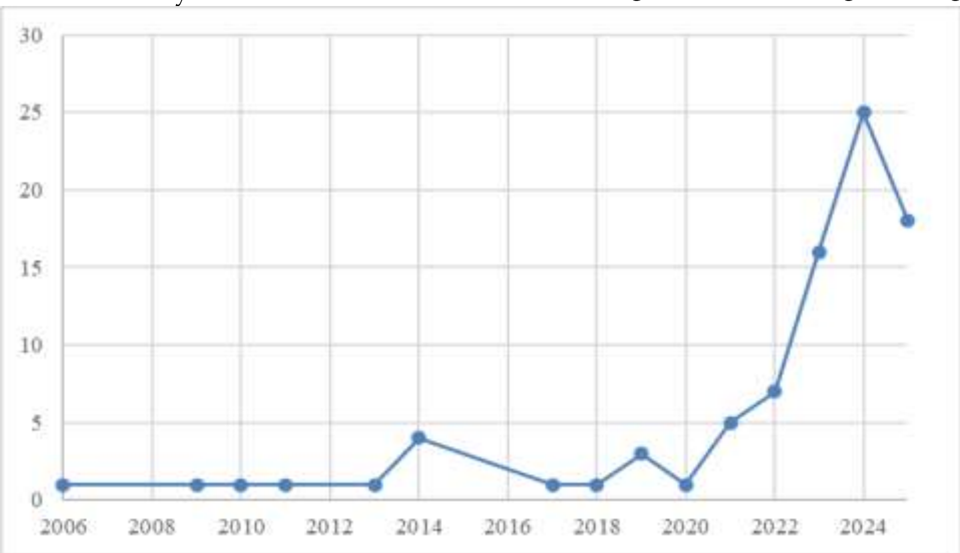

Figure 2: Number of publication (n).

The integration period (2014-2020) demonstrates gradual research expansion with periodic fluctuations, reaching a notable peak of four publications in 2014 that corresponded directly to Paris Agreement negotiations and increased global climate commitments. This phase witnessed the emergence of digital technology convergence with environmental markets, as evidenced by studies such as García-Alvarado et al. (2014) who explored emission trading schemes in closed-loop systems, and Sitdikova (2014) who examined domestic emissions trading possibilities. Research during this period began incorporating blockchain applications and IoT systems for carbon tracking, with Yang et al. (2019) investigating how digital platforms could enhance remanufacturing operations within carbon trading frameworks. The integration phase established technological feasibility while demonstrating initial circular economy applications that could generate tradeable environmental credits.

The contemporary acceleration period (2021-2025) demonstrates exponential growth, surging dramatically from 5 publications in 2021 to 25 in 2024, indicating that digital carbon markets within circular economy contexts have emerged as a critical research priority. This surge reflects the convergence of urgent decarbonization imperatives with technological readiness, as demonstrated by recent studies including Xu et al. (2021) who developed robust models for global reverse logistics networks under carbon trading, Ahmad & Hassan (2022) who explored carbon credit mechanisms in sustainable aquaculture, and López-Pacheco et al. (2021) who investigated CO2 phyco-capture as carbon credit generation strategies. The recent acceleration is further supported by comprehensive frameworks developed by Alshammari et al. (2025) examining AI and ESG circular economies in carbon trading contexts, and Vandana & Cerchione (2025) who assessed carbon trading impacts on circular supply chain profitability.

The thematic analysis reveals distinct research focus areas that emerged during each development phase, as systematically organized in Table 2. The progression demonstrates how early theoretical foundations evolved into sophisticated technological implementations, with recent studies emphasizing practical deployment strategies and stakeholder engagement mechanisms. Tsai & Lin (2024) and Cheng & Wang (2023) exemplify contemporary research focusing on carbon tax integration with circular supply chains, while Rabbi (2025) and Raman et al. (2025) demonstrate advanced applications in food systems and textile industries respectively.

Table 2: Research Themes by Development Phases.

Phase	Core Themes	Key Focus Areas	Publications
Foundational (2006-2013)	Basic Carbon Trading Circular Economy Concepts	• Traditional carbon market structures • Linear-to-circular transitions • Policy framework development	8
Integration (2014-2020)	Blockchain for Carbon IoT Monitoring Systems Emission Trading Schemes Waste-to-Energy	• Digital technology convergence • Automated verification systems • Smart contract applications • Preliminary circular implementations	25
Implementation (2021-2025)	Digital Platforms Smart Contracts AI & Machine Learning Closed-Loop Supply Chains	• Practical deployment strategies • Stakeholder participation frameworks • Real-time monitoring systems • Comprehensive market integration	53

The evolution pattern shown in Table 1 demonstrates a clear progression from theoretical foundations through technological integration to practical implementation. The foundational period's 8 studies, including pioneering work by Barrett et al. (2013) on consumption-based emissions accounting and Gupta & Palsule-Desai (2011) on sustainable supply chain frameworks, established essential theoretical groundwork. The integration period's 25 studies introduced digital technologies and automation concepts, with significant contributions from Noya et al. (2017) on circular economy environmental credits and Millward-Hopkins & Purnell (2019) on carbon-neutral biofuels. The contemporary period's 53 studies focus on scalable deployment strategies and comprehensive stakeholder engagement, representing the highest research density and innovation focus. Current research emphasizes overcoming implementation barriers including regulatory uncertainty, technology literacy gaps, and high transaction costs while developing standardized approaches for global scaling across diverse stakeholder groups and geographic contexts, as demonstrated by recent comprehensive studies from Singh Kharayat & Gupta (2025) and Wang et al. (2024).

4.2. Geographic Distribution and Sectoral Analysis

The geographic distribution of research reveals significant disparities in digital carbon markets and circular economy integration studies, with distinct regional clusters of research activity emerging across different continents. As illustrated in the global research distribution map (Figure 3), China emerges as the dominant research hub, reflecting the country's aggressive carbon neutrality commitments and extensive pilot circular economy policies as demonstrated by Xie et al. (2024) who evaluated circular economy pilot policy impacts on green total factor productivity, and Lingrong et al. (2023) who examined carbon quota and trading mechanisms in recycling contexts. European leadership is evident through Germany's focus on industrial symbiosis and technology integration (Fröhling et al., 2009), Italy's emphasis on bioeconomy applications and waste valorization (Labianca et al., 2024; Vilarinho et al., 2025), and Spain's agricultural integration approaches (Noya et al., 2017; Pergola et al., 2023). The United States primarily addresses policy frameworks and financial mechanisms (Barrett et al., 2013; Preuss & You, 2024), while developing economies remain critically underrepresented despite being major carbon emitters, indicating substantial knowledge gaps in climate finance accessibility and technology transfer mechanisms for emerging markets where digital carbon market participation could drive significant environmental and economic benefits.

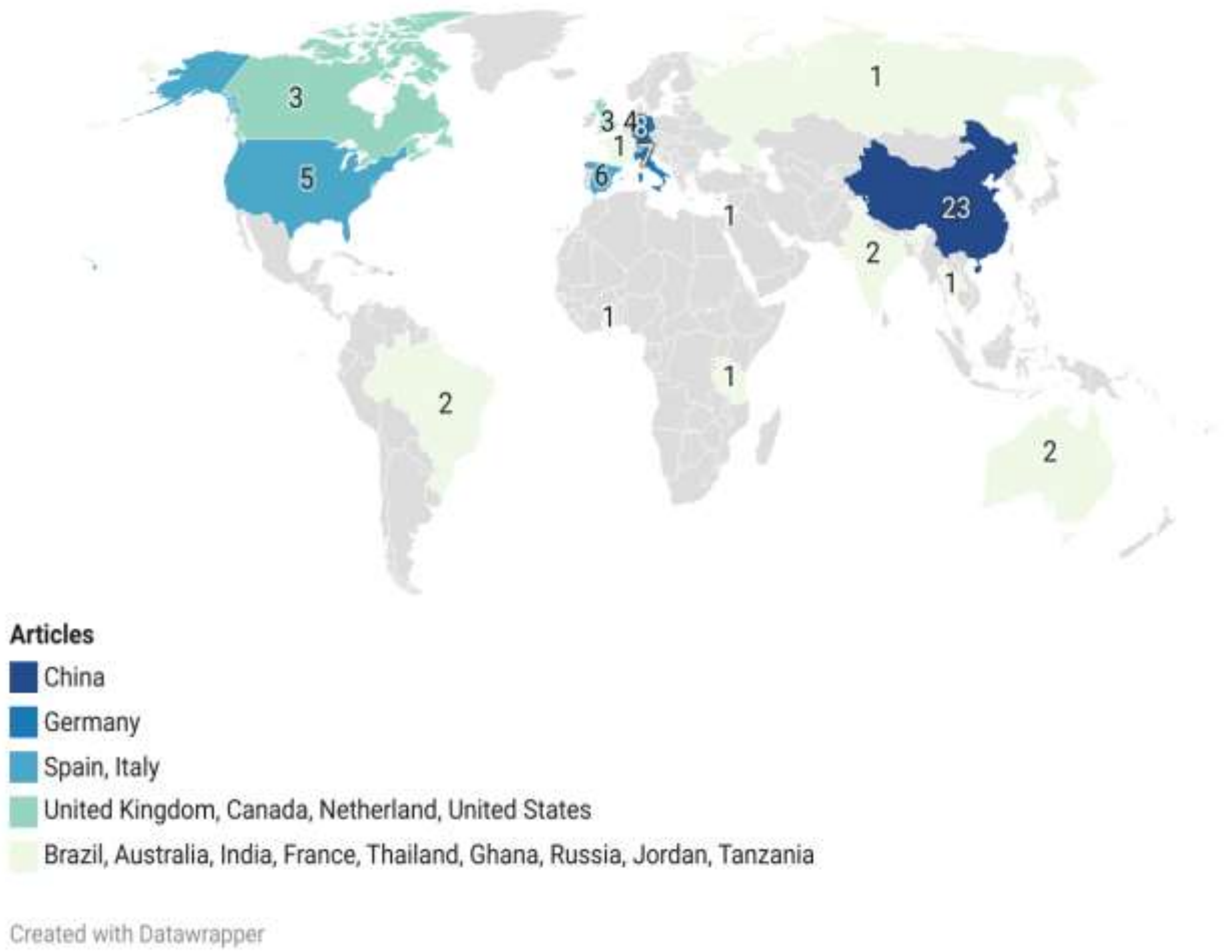

Figure 3: Geographical Distribution.

The geographical visualization in Figure 3 clearly demonstrates the concentration of research activity in developed economies, with China's dark blue coloring reflecting its dominant position, followed by the medium blue representation of Germany and the lighter blue tones indicating moderate research activity across Western Europe and North America. The map reveals concerning gaps in research coverage across Africa, Latin America, and much of Asia, where only isolated studies exist despite these regions facing significant climate adaptation challenges and carbon reduction opportunities. This geographic imbalance, as detailed in Table 3, suggests that digital carbon market research remains predominantly concentrated in countries with established carbon trading infrastructure and advanced technological capabilities, potentially limiting the global applicability and transferability of research findings to diverse economic and technological contexts.

Table 3: Geographic Distribution of Research.

Country	Number of Studies	Representative Studies
China	23	Xie et al. (2024); Lingrong et al. (2023); Chen et al. (2024); Xu & Shang (2023)
Germany	8	Fröhling et al. (2009); Kunz & Blanke (2022); Falk et al. (2021)
Italy	7	Labianca et al. (2024); Vilarinho et al. (2025); D'Adamo et al. (2023); Elattar et al. (2025)
Spain	6	Noya et al. (2017); Pergola et al. (2023); Fernández-Ríos et al. (2023)
United States	5	Barrett et al. (2013); Preuss & You (2024); Millward-Hopkins & Purnell (2019)
Netherlands	4	Xu et al. (2021); Dalton et al. (2023)
United Kingdom	3	Al-Habaibeh et al. (2018); Gupta & Palsule-Desai (2011)
Canada	3	Chegounian et al. (2024); Pereira et al. (2023)
Brazil	2	Pereira et al. (2023); Deprá et al. (2022)
Australia	2	Jayawickrama et al. (2024); Dalton et al. (2023)
Other Countries	8	Various single-country studies
Multi-country/Global	15	Comparative and international framework studies

The sectoral analysis presented in Table 4 reveals manufacturing and industrial processes dominating research focus, emphasizing high carbon intensity sectors where circular economy applications demonstrate greatest potential for emission reductions through closed-loop production systems as shown by Vandana & Cerchione (2025) and comprehensive emission trading schemes analyzed by Cheng & Wang (2023). Energy and utilities represent the second major research concentration, particularly focusing on waste-to-energy integration (Fava et al., 2025; Nahwani et al., 2024) and renewable system optimization that create dual benefits of waste reduction and carbon credit generation. Construction emerges as a critical sector reflecting growing recognition of embodied carbon challenges and material circularity opportunities demonstrated by Kaewunruen et al. (2025) and Poolsawad et al. (2023). Notably, the agricultural and food systems sector receives disproportionately limited attention despite contributing approximately 24% of global emissions, with only limited studies like Rabbi (2025) and Ahmad & Hassan (2022) exploring carbon credit mechanisms in food production, suggesting a significant research gap where digital carbon markets could revolutionize sustainable agriculture practices and food waste valorization.

Table 4: Sectoral Distribution of Research.

Sector	Number of Studies	Representative Studies
Manufacturing & Industrial	31	Vandana & Cerchione (2025); Cheng & Wang (2023); Zhou et al. (2022); Tsai & Lin (2024)
Energy & Utilities	18	Fava et al. (2025); Nahwani et al. (2024); Al-Habaibeh et al. (2018); Falk et al. (2021)
Construction & Built Environment	12	Kaewunruen et al. (2025); Poolsawad et al. (2023); Labianca et al. (2024); Laveglia et al. (2024)
Agriculture & Food Systems	8	Rabbi (2025); Ahmad & Hassan (2022); Patel et al. (2025); Pradhan & Meena (2023)
Transportation & Logistics	6	Xu et al. (2021); Li et al. (2025); Jaradat et al. (2025)
Waste Management	5	Ottani et al. (2024); Jayawickrama et al. (2024); Ansar et al. (2025)
Financial Services	3	Pan et al. (2022); Federico & Adamo (2024); Sazonets et al. (2024)
Technology & Digital Services	2	Alshammari et al. (2025); Raman et al. (2025)
Multi-sectoral Applications	1	Cross-sector integration framework

4.3. Technology Enablers and Digital Platform Infrastructure

Digital carbon markets rely on sophisticated infrastructure enabling automated verification, real-time monitoring, and seamless stakeholder participation (Appendix A). AI and machine learning applications serve as critical enablers for carbon market analysis and predictive modeling (Alshammari et al., 2025), while IoT and big data technologies facilitate real-time emission monitoring and precision agriculture, achieving up to 77,826 tons CO_2 equivalent reduction annually (Patel et al., 2025; Nahwani et al., 2024). Digital twin technology represents a paradigm shift in infrastructure lifecycle management, enabling cradle-to-cradle carbon management and strategic material reuse planning (Kaewunruen et al., 2025). Blockchain provides essential supply chain traceability and carbon credit verification for circular economy applications (Raman et al., 2025; Pestana et al., 2025). However, significant implementation gaps persist in technology literacy and standardization protocols, indicating that widespread adoption requires comprehensive stakeholder capacity building and regulatory harmonization.

Carbon trading platforms represent the operational core of digital carbon markets, with cap-and-trade systems demonstrating proven effectiveness in enhancing green technology investments and supply chain sustainability (Vandana & Cerchione, 2025). Carbon pricing mechanisms face challenges with price volatility (78-91 €/tCO_2) and cross-border coordination (D'Adamo et al., 2023), while carbon tariffs show greater effectiveness in encouraging emission reductions (Li et al., 2025). Digital marketplaces for resource exchange remain nascent but promising, with Industry 4.0-integrated platforms facilitating secondary raw material exchange and industrial symbiosis (Pestana et al., 2025).

Measurement and verification systems provide essential credibility through LCA methodologies and standardized MRV protocols. Carbon capture and utilization technologies achieve 46-52% GHG emission reductions in food production (Fernández-Ríos et al., 2023), while standardized LCA procedures ensure carbon credit validity for anaerobic digestion applications (Jayawickrama et al., 2024). Material flow analysis enables carbon footprint tracking, with potential 11-million-ton

GHG reductions worth $67 million in carbon credits demonstrated in Thailand's construction sector (Poolsawad et al., 2023), highlighting substantial financial incentives through comprehensive material circularity measurement.

4.4. Circular Economy Applications and Implementation Strategies

Circular economy applications within digital carbon markets transform waste streams into valuable carbon credits while advancing resource circularity (Appendix B). Waste-to-energy and biogas applications emerge as the most prominent implementation, with biogas production from livestock, municipal, and agricultural waste offering substantial carbon reduction potential. Pig waste biogas systems generate electricity while creating carbon credit commercialization opportunities and rural energy security (Pereira et al., 2023). Biogas capacity of 1.5 MW can produce 13,140 MWh annually, reducing 77,826 tons CO_2 equivalent with potential carbon trading value of USD 3,113,040 per year (Nahwani et al., 2024). Biomethane production in sugarcane biorefineries achieves IRR exceeding 35% with 2–6-year payback periods (Fava et al., 2025), while green hydrogen production from wastewater treatment reaches carbon intensities as low as 5.79 gCO_2e/MJ (Chegounian et al., 2024).

Material recovery and recycling applications address resource scarcity and carbon emission reduction through sophisticated supply chain integration. Global plastic waste recycling networks account for currency and carbon trading price uncertainties (Xu et al., 2021), achieving net reduction of 8.27 million metric tons CO_2 equivalent (Liu et al., 2021). Metal recovery from waste catalysts achieves over 40% CO_2 emission savings, generating approximately 2 million USD annually in carbon credits (Amato et al., 2025). Construction material reuse demonstrates innovative embodied carbon reduction, with biochar-incorporated concrete reaching -720 kg CO_2/tonne savings (Labianca et al., 2024) and bivalve shell waste in ceramics reducing emissions by 10-14% (Vilarinho et al., 2025).

Closed-loop supply chains and nature-based solutions represent sophisticated integration approaches combining circular economy principles with digital carbon mechanisms. Remanufacturing applications show sector-specific potential, with electric vehicle battery recycling preventing up to six tons CO_2 emissions per ton while saving $300 per ton (Zhou et al., 2022; Jaradat et al., 2025). Industrial symbiosis facilitates cross-sector waste valorization through standardized frameworks (Pestana et al., 2025; Vilarinho et al., 2025). Nature-based solutions provide biological carbon sequestration, with global bivalve aquaculture producing 13.6 million metric tons shell calcium carbonate annually (Alonso et al., 2021) and 94,847 tons microalgae biomass potentially balancing Mexico City's CO_2 emissions (López-Pacheco et al., 2021).

Composting and soil management applications demonstrate carbon sequestration potential while creating economic value through waste valorization. Integrated industrial waste composting achieves 47.5 Mg ha^{-1} CO_2 sequestration worth US$ 1,899 ha^{-1} (Pradhan & Meena, 2023), while biochar integration in municipal composting generates 3,652 carbon credits through VERRA methodology and reduces methane emissions by nearly half (Ottani et al., 2024). Economic viability shows positive net present values of $64,243-$154,096 (Ansar et al., 2025), with benefit-cost ratios exceeding 1 and internal rates of return greater than 28% (Banunle et al., 2024), establishing composting as a viable pathway for environmental and economic returns.

4.5. Stakeholder Participation Patterns and Engagement Mechanisms

Stakeholder participation patterns reveal distinct engagement mechanisms across organizational scales, with varying entry barriers, technological requirements, and value creation opportunities aligning with Theory of Change pathways. Individual and SME participation represents the foundational level, characterized by entry-level strategies focusing on micro-investment opportunities and basic circular economy applications. Technology literacy gaps and insufficient regulatory frameworks constrain SME participation (Singh Kharayat & Gupta, 2025), while small enterprises struggle with complex carbon accounting methodologies and blockchain-based trading platforms (Tsai et al., 2023). Micro-investment opportunities typically involve household waste composting (Ansar et al., 2025), small-scale renewable energy projects with carbon credit generation (Falk et al., 2021), and community-based material recovery programs providing modest but consistent carbon trading revenues.

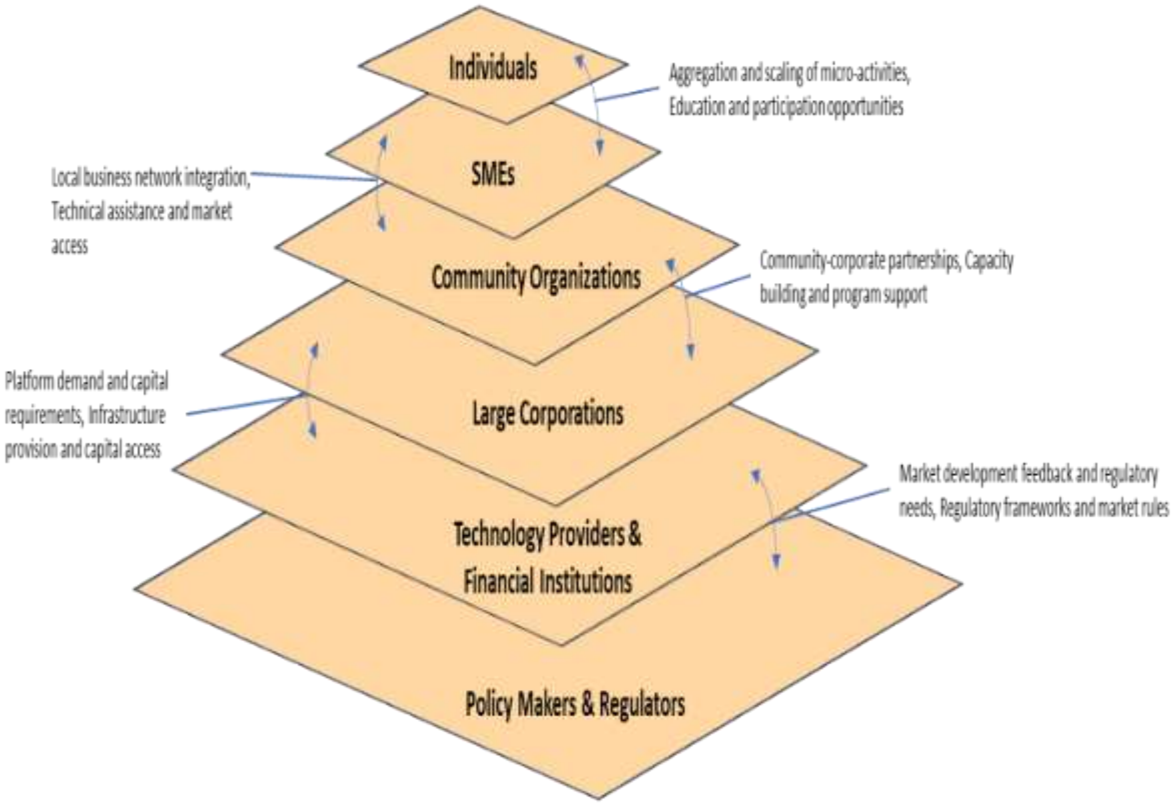

Figure 4: Digital Carbon Market Stakeholder Engagement Framework.

Digital literacy represents a critical barrier for individual and SME participation, with substantial gaps in understanding blockchain-based carbon platforms, carbon accounting methodologies, and circular economy integration preventing effective market engagement. Cost-benefit considerations involve modest initial investments ranging from household-scale composting systems generating 0.7 t CO_2/ha/year sequestration (Kunz & Blanke, 2022) to small renewable energy installations with carbon credit revenues. However, transaction costs often exceed potential benefits for individual participants, necessitating aggregation mechanisms and simplified participation platforms to achieve economic viability.

Enterprise and corporate participation represent the intermediate engagement level, characterized by corporate carbon strategy integration encompassing comprehensive supply chain carbon management and sophisticated risk management approaches (Figure 5). Large corporations demonstrate advanced capabilities through closed-loop supply chain implementations, with carbon trading policies significantly enhancing green technology investments when integrated with circular economy principles (Vandana & Cerchione, 2025). Manufacturing companies choose remanufacturing strategies based on carbon trading prices, with high prices favoring in-house approaches (Zhou et al., 2022). Corporate supply chain carbon management enables 11-million-ton GHG reductions worth approximately $67 million in carbon credit potential (Poolsawad et al., 2023).

Risk management approaches focus on carbon price volatility and regulatory uncertainty, with EUA price variations between 78-91 €/tCO_2 requiring sophisticated hedging strategies (D'Adamo et al., 2023). Market value creation involves multiple revenue streams including carbon credit sales, resource cost reductions, and brand value enhancement through sustainability leadership. Carbon-constrained closed-loop supply chains increase profitability while reducing emissions when properly implemented (Cheng & Wang, 2023), while cross-border carbon adjustments create competitive advantages for companies with advanced emission reduction capabilities (Li et al., 2025).

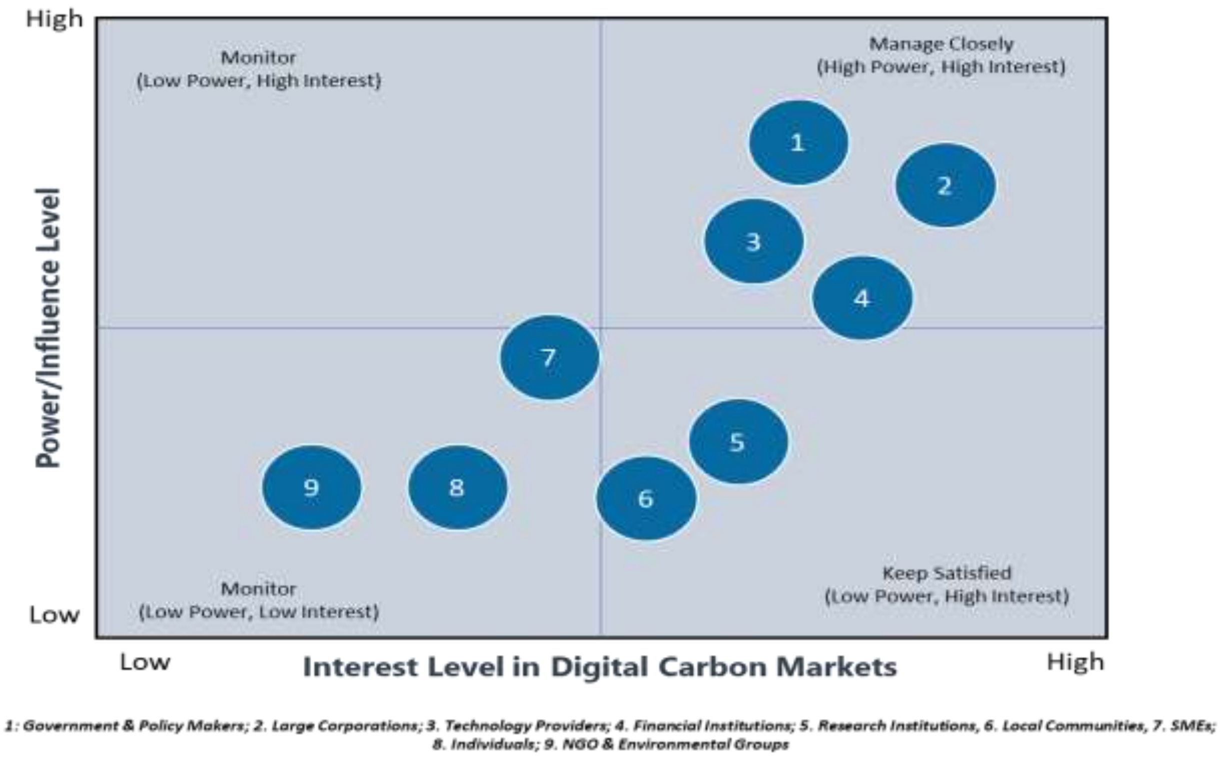

Figure 5: Stakeholder Power-Interest Matrix: Digital Carbon Markets.

Institutional and government participation constitutes the highest stakeholder engagement level, characterized by comprehensive policy framework development, regulatory compliance mechanisms, and market facilitation roles creating enabling environments for digital carbon market development. Government participation involves carbon quota allocation, emission trading scheme design, and international coordination, with circular economy pilot policies significantly enhancing green total factor productivity when properly implemented (Xie et al., 2024). Government subsidies and carbon trading schemes effectively promote low-carbon technology diffusion through supply networks (Wang et al., 2024), while regulatory compliance mechanisms ensure market integrity and environmental additionality.

The stakeholder power-interest matrix (Figure 6) illustrates complex dynamics between participant categories, positioning governments and large corporations in the "manage closely" quadrant due to high power and interest levels, while technology providers and financial institutions occupy critical enabling positions with high interest but variable power depending on market maturity. Public procurement strategies represent powerful market creation mechanisms, with governments leveraging purchasing power to create demand for low-carbon products generating carbon credits. Public sector adoption of standardized waste supply chain frameworks accelerates private sector participation and industrial symbiosis development (Pestana et al., 2025). Market facilitation roles include technical assistance, standardization development, and financial incentives reducing participation barriers across stakeholder categories.

Successful digital carbon market development requires coordinated engagement across all stakeholder levels, with government policy creating enabling conditions, corporate participation providing market scale and technical capability, and individual/SME participation ensuring broad-based adoption and social acceptance. However, significant gaps persist in coordination mechanisms and equitable benefit distribution, suggesting future research should focus on developing inclusive participation frameworks that address diverse needs, capabilities, and constraints across the stakeholder spectrum while maintaining environmental integrity and economic viability.

5. DISCUSSION

The synthesis of findings from this systematic literature review reveals the complex multi-dimensional nature of digital carbon markets and circular economy integration, requiring coordinated analysis across technical, economic, social, and policy perspectives to understand the full implications for stakeholder participation strategies. The technical perspective demonstrates that digital carbon platforms serve as critical innovation infrastructure that aligns directly with SDG 9 (Industry, Innovation and Infrastructure) through the development of sophisticated technological ecosystems. Alshammari et al. (2025) revealed how AI and ESG circular economy indices create robust platforms for carbon trading with average Total Connectedness Index of 60%, while Pestana et al. (2025) developed standardized waste supply chain frameworks utilizing Industry 4.0 paradigms that facilitate industrial symbiosis through digital marketplaces. The integration of AI, IoT, and blockchain technologies enables sustainable industrialization as demonstrated by Patel et al. (2025) who achieved significant carbon footprint reductions in mushroom production through integrated sensors and machine learning, and Kaewunruen et al. (2025) who pioneered BIM-driven digital twins for comprehensive lifecycle carbon management in infrastructure development.

However, the technical perspective also reveals critical challenges in technology transfer and capacity building that constrain widespread adoption, particularly in developing economies where Singh Kharayat & Gupta (2025) identified insufficient regulatory frameworks and lack of clean technology as primary barriers to low-carbon technology implementation. The platform integration capabilities demonstrate strong alignment with SDG 17 (Partnerships for the Goals) through multi-stakeholder collaboration facilitation, with Raman et al. (2025) showing how blockchain-based supply chains enable comprehensive stakeholder engagement in textile circular economy applications, while Falk et al. (2021) illustrated how technology sharing and knowledge transfer can bridge development gaps in rural electrification projects that generate carbon credits.

The economic perspective reveals substantial opportunities for decent work creation and economic growth that directly support SDG 8 objectives, with green jobs emerging through circular economy implementations across diverse sectors. Banunle et al. (2024) demonstrated how biomass composting investments achieve benefit-cost ratios exceeding 1 and internal rates of return greater than 28%, while Pereira et al. (2023) showed how pig waste biogas systems create multiple revenue streams including electricity generation, carbon credit commercialization, and rural energy security enhancement. The economic viability of carbon trading mechanisms shows promising potential, with Fava et al. (2025) achieving IRR values exceeding 35% in biomethane production and Nahwani et al. (2024) generating potential carbon trading values reaching USD 3,113,040 annually from biogas operations. However, SME participation faces significant economic barriers, with Tsai et al. (2023) revealing how complex carbon accounting methodologies and high transaction costs prevent effective small-scale engagement in carbon markets.

The alignment with SDG 12 (Responsible Consumption and Production) emerges through comprehensive waste reduction strategies that generate substantial carbon credits, with Rabbi (2025) demonstrating how EU food system optimization could achieve significant emission reductions while Ottani et al. (2024) showed how biochar integration in municipal composting generates 3,652 carbon credits through VERRA methodology. Circular business models enable sustainable consumption patterns as evidenced by Raman et al. (2025) who implemented AI-driven roadmaps for textile industry circular economy adoption and Saccani et al. (2024) who developed emission-based pricing mechanisms for product-service systems. Resource efficiency improvements show substantial scale potential, with Poolsawad et al. (2023) quantifying 11 million ton GHG reduction potential in Thailand's construction sector worth approximately $67 million in carbon credit value, while contributing to poverty alleviation objectives under SDG 1 through rural income generation opportunities demonstrated by Pereira et al. (2023) and economic development in emerging economies as shown by Falk et al. (2021) in Tanzania's rural electrification context.

The social perspective reveals critical challenges in equitable participation that directly relate to SDG 10 (Reduced Inequalities) through digital divide constraints that limit carbon market access for marginalized communities. Singh Kharayat & Gupta (2025) identified technology literacy gaps as fundamental barriers to participation, while regional variations in implementation capacity create unequal access to carbon market benefits as demonstrated by Rabbi (2025) in European food systems and Xie et al. (2024) in Chinese circular economy pilot regions. The development of inclusive participation mechanisms remains a critical challenge, with Falk et al. (2021) highlighting how electricity pricing of €1.30/kWh proves prohibitive for widespread household adoption despite technical feasibility of renewable energy systems. Educational requirements for effective participation align with SDG 4 (Quality Education) through digital literacy development needs and comprehensive capacity building programs, as evidenced by Dalton et al. (2023) who emphasized the importance of multidisciplinary approaches and skill development for circular economy implementation in housing industry contexts.

The policy perspective demonstrates the

fundamental importance of robust governance frameworks that support SDG 16 (Peace, Justice and Strong Institutions) through transparent and accountable carbon trading systems. D'Adamo et al. (2023) revealed how governance frameworks must address carbon leakage risks and ensure competitive market conditions, while Tao et al. (2024) demonstrated how environmental policy design requires careful balance between economic and environmental objectives through multi-criteria approaches. Pestana et al. (2025) emphasized the critical role of standardized processes and open data governance in ensuring supply chain transparency and preventing fraud in carbon credit systems. The regulatory frameworks must address anti-fraud mechanisms and market integrity to maintain stakeholder confidence and environmental additionality.

Climate action objectives under SDG 13 require sophisticated policy instruments for emission reduction, with Li et al. (2025) demonstrating how carbon tariffs prove more effective than carbon trading prices in encouraging emission reductions, while Cheng et al. (2025) revealed how government subsidies and carbon trading schemes can effectively promote low-carbon technology diffusion when properly coordinated. Carbon pricing mechanisms show variable effectiveness depending on implementation context, with Vandana & Cerchione (2025) finding that carbon trading policies significantly enhance green technology investments when integrated with circular economy principles, and Xu & Shang (2023) revealing how emission taxation policies and green finance initiatives positively influence mineral resource efficiency. International cooperation remains essential for achieving global climate goals, as demonstrated by Olawade et al. (2025) who emphasized the necessity of harmonizing space exploration objectives with environmental preservation through integrated technological innovation and international cooperation frameworks.

The integration of these multi-dimensional perspectives demonstrates that effective digital carbon market development requires simultaneous attention to technical innovation, economic viability, social equity, and policy coherence to achieve meaningful progress toward sustainable development objectives. As illustrated in the SDG Integration Framework (Figure 6), the interconnected nature of these challenges necessitates holistic approaches that recognize the central role of digital carbon markets in advancing multiple SDG targets simultaneously. The framework positions SDG 13 (Climate Action) at the apex as the primary environmental objective, while SDG 9 (Industry, Innovation and Infrastructure) and SDG 17 (Partnerships for the Goals) provide the technical and collaborative foundations necessary for implementation.

Figure 6: SDG Integration Framework for Digital Carbon Markets & Circular Economy.

The economic dimension encompasses SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 1 (No Poverty), emphasizing how circular economy integration within digital carbon markets can create sustainable livelihoods while reducing environmental impacts. The social dimension addresses equity concerns through SDG 10 (Reduced Inequalities), SDG 4 (Quality Education), and SDG 5 (Gender Equality), recognizing that inclusive participation requires targeted interventions to overcome digital divides and capacity constraints. The governance dimension emphasizes SDG 16 (Peace, Justice and Strong Institutions) as fundamental to maintaining market integrity and stakeholder confidence in carbon trading systems.

6. CONCLUSIONS

This systematic literature review comprehensively examined effective participation strategies in digital carbon markets through circular economy integration, analyzing 86 studies published between 2006-2025. The research reveals that digital carbon markets represent a paradigmatic shift in carbon trading through blockchain, AI, and IoT technologies that enable automated verification, real-time monitoring, and transparent trading mechanisms. The integration with circular economy principles creates synergistic opportunities where waste-to-energy projects, material recovery initiatives, and nature-based solutions generate tradeable carbon credits while advancing resource circularity. The analysis demonstrates significant geographic disparities with China leading research activity (23 studies), followed by European nations, while developing economies remain underrepresented despite substantial carbon reduction potential. Manufacturing and industrial sectors dominate research focus (31 studies), emphasizing high carbon intensity applications, while agricultural sectors receive limited attention despite contributing 24% of global emissions. Technology enablers including AI, IoT, blockchain, and digital twins provide essential infrastructure, though implementation gaps persist in technology literacy and standardization protocols.

Stakeholder participation patterns reveal distinct engagement mechanisms across organizational scales, with individual/SME participation constrained by technology literacy gaps and high transaction costs, while enterprise participation demonstrates advanced capabilities through closed-loop supply chain implementations. Government participation remains critical for policy framework development and market facilitation. The multi-dimensional analysis across technical, economic, social, and policy perspectives demonstrates alignment with multiple SDG targets, particularly SDG 13 (Climate Action), SDG 9 (Industry, Innovation), and SDG 12 (Responsible Consumption), emphasizing the need for integrated approaches that simultaneously address technical scalability, economic accessibility, social inclusivity, and policy coherence.

7. LIMITATIONS AND FUTURE RESEARCH

This study acknowledges several limitations that provide opportunities for future research. First, the systematic review was limited to English-language publications in the Scopus database, potentially excluding relevant studies in other languages or databases, particularly from developing countries where digital carbon market applications may be emerging. Second, the rapid evolution of digital technologies and carbon market mechanisms means that recent developments may not be fully captured in published literature, suggesting need for real-time monitoring of industry developments and pilot projects. Third, the predominant focus on developed economies in existing literature limits understanding of implementation challenges and opportunities in developing countries where carbon market participation could drive significant environmental and economic benefits. Future research should prioritize case studies and empirical investigations in emerging economies to develop context-specific participation strategies and technology transfer mechanisms.

Fourth, the analysis revealed significant sectoral gaps, particularly in agricultural and food systems where only 8 studies were identified despite the sector's substantial carbon footprint. Future research should explore digital carbon market applications in agriculture, focusing on precision farming, regenerative practices, and food waste valorization opportunities. Fifth, the literature lacks longitudinal studies examining the long-term effectiveness and sustainability of digital carbon market participation strategies. Future research should conduct multi-year assessments of stakeholder engagement mechanisms, technology adoption patterns, and economic returns to develop evidence-based best practices. Finally, the integration of social equity considerations in digital carbon market design remains underdeveloped. Future research should investigate inclusive participation frameworks that address digital divides, capacity building requirements, and equitable benefit distribution mechanisms to ensure that carbon market development contributes to social justice objectives alongside environmental goals.

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APPENDICES

Appendix A: Technology Enablers and Platform Infrastructure.

Technology Category	Specific Technologies	Studies	Key Applications	Representative Studies
Digital Technologies	AI & Machine Learning	15	Carbon market analysis, predictive modeling	Alshammari et al. (2025); Patel et al. (2025); Chen et al. (2024)
	IoT & Big Data	12	Real-time monitoring, precision agriculture	Patel et al. (2025); Nahwani et al. (2024); Kaewunruen et al. (2025)
	Digital Twin Technology	3	Lifecycle management, carbon optimization	Kaewunruen et al. (2025)
	Blockchain	8	Supply chain traceability, verification	Raman et al. (2025); Pestana et al. (2025)
Carbon Trading Platforms	Cap-and-Trade Systems	18	ETS implementation, quota allocation	Vandana & Cerchione (2025); Wang & Shao (2022); Xie et al. (2024)
	Carbon Pricing Mechanisms	14	Price analysis, cross-border adjustments	D'Adamo et al. (2023); Li et al. (2025); Tao et al. (2024)
	Digital Marketplaces	6	Stakeholder connection, resource exchange	Pestana et al. (2025); Federico & Adamo (2024)
Measurement & Verification	Carbon Accounting Tools	16	LCA integration, MRV protocols	Fernández-Ríos et al. (2023); Jayawickrama et al. (2024); Poolsawad et al. (2023)
	Material Flow Analysis	8	Carbon footprint tracking	Poolsawad et al. (2023); Dalton et al. (2023); Liu et al. (2021)

	Carbon Intensity Calculators	5	Pathway assessment, impact quantification	Chegounian et al. (2024); Rabbi (2025); Castagnoli et al. (2024)

Appendix B: Circular Economy Applications and Carbon Market Integration.

Application Category	Specific Applications	Studies	Carbon Impact Range	Representative Studies
Waste-to-Energy & Biogas	Biogas Production	12	13,140-77,826 tons CO_2 eq/year	Pereira et al. (2023); Nahwani et al. (2024); Fava et al. (2025)
	Biomethane Generation	4	IRR >35%, 2-6 year payback	Fava et al. (2025)
	Green Hydrogen Production	3	5.79-21.4 gCO_2 e/MJ	Chegounian et al. (2024)
Material Recovery & Recycling	Plastic Waste Recycling	6	8.27 million tons CO_2 eq net reduction	Xu et al. (2021); Liu et al. (2021)
	Metal Recovery	4	>40% CO_2 savings, $2M credits/year	Amato et al. (2025); Fröhling et al. (2009)
	Construction Material Reuse	8	-720 to +53 kg CO_2 eq/tonne	Labianca et al. (2024); Vilarinho et al. (2025)
Composting & Soil Management	Industrial Waste Composting	7	47.5 Mg CO_2 /ha sequestration	Pradhan & Meena (2023); Ottani et al. (2024)
	Biodegradable Waste	5	$64K-$154K NPV potential	Ansar et al. (2025); Banunle et al. (2024)
	Agricultural Applications	4	0.7 t CO_2 /ha/year sequestration	Kunz & Blanke (2022)
Closed-Loop Supply Chains	Remanufacturing	15	Variable by sector	Zhou et al. (2022); Jaradat et al. (2025)
	Industrial Symbiosis	8	Cross-sector emission reduction	Vilarinho et al. (2025); Pestana et al. (2025)
	Product-Service Systems	3	Emission-based revenue models	Saccani et al. (2024)
Nature-Based Solutions	Aquaculture Integration	4	13.6 million tons shell $CaCO_3$ /year	Alonso et al. (2021); Ahmad et al. (2022)
	Microalgae Systems	3	94,847 tons biomass for CO_2 balance	López-Pacheco et al. (2021); Ahmad et al. (2022)
	Bioremediation	2	Soil carbon + contamination remediation	Warra & Prasad (2023)