International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(REVIEW ARTICLE)

Check for updates

Sustainable and digital transformation of international agri-food supply chains

T. N. S. Samarawickramage *

Department of Business and Management, Chester Business School, University of Chester, United Kingdom.

International Journal of Science and Research Archive, 2026, 19(03), 663-673

Publication history: Received on 06 May 2026; revised on 13 June 2026; accepted on 16 June 2026

Article DOI: https://doi.org/10.30574/ijsra.2026.19.3.1337

Abstract

The convergence of digital innovation and sustainability imperatives has fundamentally reshaped how international agri-food supply chains are conceptualised, governed, and operationalised. Escalating climate commitments, proliferating environmental regulation, and mounting pressure from investors and consumers have elevated Scope 3 greenhouse gas emissions measurement and deforestation compliance from voluntary ambitions to legal necessities. Simultaneously, technologies including blockchain, the Internet of Things (IoT), artificial intelligence (AI), and digital twin modelling are creating unprecedented capacity for end-to-end supply chain visibility. Yet a critical gap persists: existing scholarship has examined digital transformation and sustainability transitions largely in isolation, and the mechanisms through which digital tools can operationalise Scope 3 Category 1 emissions measurement and regulatory compliance across complex, multi-tier international agri-food chains remain insufficiently understood.

This paper develops an integrative conceptual framework connecting digital transformation capability, sustainability governance, and regulatory compliance in the agri-food context. Drawing on a systematic literature review of 87 peer-reviewed studies published between 2010 and 2025, supplemented by analysis of regulatory documents including the GHG Protocol Corporate Value Chain Standard, WRAP Scope 3 Protocols, and the European Union Deforestation Regulation (EUDR), three principal research questions are formulated and addressed. Results reveal five interconnected thematic clusters: fragmentation of Scope 3 measurement methodologies; the traceability gap in multi-tier supplier networks; enabling and inhibiting conditions for digital technology adoption; the institutional governance vacuum around mandatory disclosure; and distributional asymmetries between large operators and smallholder producers. The discussion develops a Digital Sustainability Governance Model and identifies priority research and policy directions. Effective sustainable digital transformation requires not merely technological capability but the simultaneous evolution of governance structures, data standards, and inclusive institutional arrangements.

Keywords: Agri-Food Supply Chains; Digital Transformation; Scope 3 Emissions; Sustainability; Blockchain; Iot; EUDR; Decarbonisation

1. Introduction

International agri-food supply chains are among the most complex and consequential systems in the global economy. Spanning multiple continents, tiers of production, processing, logistics, and retail, these chains collectively account for approximately one-third of global anthropogenic greenhouse gas (GHG) emissions and are the primary driver of tropical deforestation, freshwater depletion, and biodiversity loss [1-3]. The dual pressures of climate change mitigation and the urgent need for food system resilience have made the sustainable transformation of agri-food supply chains a defining challenge of the twenty-first century.

Concurrent with these environmental imperatives, the fourth industrial revolution has produced a suite of digital technologies, blockchain, IoT sensor networks, AI-driven analytics, machine learning, and digital twin simulation, which

* Corresponding author: T. N. S. Samarawickramage

Copyright © 2026 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution License 4.0.

are progressively being integrated into supply chain management. These technologies offer transformative potential: the capacity to generate granular, real-time, and verifiable data about product provenance, environmental footprint, logistical efficiency, and regulatory compliance at a scale and depth previously unattainable [4,5]. For agri-food specifically, digitally enabled supply chain visibility could address longstanding intractability: the inability to verify on-farm conditions remotely, the data losses that occur across fragmented supplier networks, and the cost burdens of manual audit-based verification systems.

The policy landscape has evolved rapidly in response. The GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard requires organisations to account for indirect emissions across their entire value chain, including purchased goods and services (Category 1), which typically represents the largest emissions category for food and beverage companies [6,7]. More recently, the European Union Deforestation Regulation (EUDR), adopted in 2023 and enforced from December 2026 for large and medium operators, mandates that companies place on the EU market only products demonstrably free from deforestation, requiring traceability to the specific plot of land [8]. The UK is advancing its own mandatory Scope 3 disclosure framework, and WRAP's Scope 3 Protocols for Food and Drink are currently under Version 3 consultation as of 2026 [9].

Despite these converging pressures, the practical mechanisms through which digital technologies can enable credible, scalable, and cost-effective Scope 3 measurement and EUDR-type compliance in international agri-food supply chains remain poorly understood in the academic literature. This paper addresses that gap through three contributions. First, it conducts a systematic and integrative review of the existing literature, synthesising findings from 87 studies published between 2010 and 2025. Second, it develops a novel conceptual framework, the Digital Sustainability Governance Model (DSGM), that maps the relationships between digital capability maturity, emissions data quality, regulatory compliance posture, and supply chain governance structure. Third, it identifies five thematic clusters that characterise the current state of knowledge and proposes specific directions for future empirical and applied research.

The remainder of the paper is structured as follows. Section 2 presents the literature review. Section 3 identifies the research gap and states the research questions. Section 4 describes the methodology. Section 5 presents the results. Section 6 offers the discussion. Section 7 concludes with theoretical implications, practical recommendations, and future research directions.

2. Literature Review

2.1. Sustainability in Agri-Food Supply Chains

The concept of sustainable supply chain management (SSCM) emerged from the intersection of environmental management, corporate social responsibility, and operations research. Seuring and Müller [10] established an early and influential framework defining SSCM as the management of material, information, and capital flows, and cooperation among companies along the supply chain while meeting goals from all three dimensions of sustainable development. Pagell and Wu [11] empirically demonstrated that genuinely sustainable supply chains require fundamental reconceptualisation of what supply chain management is for, rather than incremental adjustments to existing practices.

Within the agri-food domain specifically, the sustainability challenge is particularly acute because the environmental impacts are concentrated upstream in agricultural production, yet decision-making power rests predominantly downstream with food manufacturers and retailers [12,13]. This structural asymmetry creates what Gold et al. [14] describe as a "sustainability blind spot" in inter-organisational relationships: the tier-one supplier communicates with the buying organisation, but the environmental and social conditions at tier-two and tier-three are effectively invisible to brand owners.

Poore and Nemecek [1], drawing on a meta-analysis of 570 studies covering more than 38,000 farms across 119 countries, found that the food system is responsible for approximately 26% of global GHG emissions, with the production stage accounting for roughly 80% of the total food system footprint. Garnett [15] distinguished between emissions arising from agricultural production processes, emissions from land-use change, and emissions from post-farm supply chain activities, providing a conceptual schema that remains foundational to applied Scope 3 accounting in the food sector.

The Scope 3 challenge in agri-food is compounded by methodological fragmentation. The GHG Protocol Scope 3 Standard defines fifteen categories of indirect value chain emissions, of which Category 1 is typically the largest for food companies, representing 70 - 90% of their total GHG inventory [16]. However, the standard permits several measurement approaches activity-based, spend-based, supplier-specific, and hybrid, each with significantly different

data requirements, accuracy levels, and implementation costs. Spend-based methods are accessible but highly inaccurate for agri-food categories, where farm-level variation in emission intensity can exceed 30-fold across the same commodity type [1]. Supplier-specific methods, while most accurate, require primary data collection from often thousands of suppliers, a logistical and cost challenge that has severely constrained adoption even among major food corporations [9].

Deforestation as a supply chain sustainability issue has attracted substantial scholarly attention. Lambin et al. [20] documented that despite over two decades of voluntary sustainability certification and corporate zero-deforestation commitments, deforestation linked to agricultural expansion continued to accelerate in key producing regions through the 2010s. The failure of private governance instruments has increasingly been attributed to traceability limitations: buyers cannot verify the origin claims of their suppliers because chain-of-custody data is discontinuous, unverified, and subject to systematic fraud [21,22].

2.2. Digital Transformation in Supply Chain Management

Contemporary treatments of digital supply chain transformation conceptualise it as an organisational process of integrating digital technology across all functions of the value chain, fundamentally altering how value is created and delivered [4,23]. The enabling technologies most relevant to agri-food supply chain transparency are blockchain distributed ledger systems, IoT sensor networks, AI and machine learning analytics, geospatial data platforms, and digital twin simulation models.

Blockchain technology has attracted particular attention as a potential solution to the provenance verification challenge in agri-food chains. Queiroz and Telles [5] characterised blockchain's unique contribution as the provision of an immutable, distributed, and transparent record of transactions. Kouhizadeh et al. [24] conducted a systematic literature review on blockchain adoption in sustainable supply chains and found that while theoretical potential is well-established, empirical evidence of large-scale deployment outcomes remains limited. Practical implementation challenges including data quality at the point of entry, interoperability between platforms, and costs of on-boarding smallholder suppliers have constrained realisation of promised benefits.

IoT sensor technology offers complementary capabilities. In agricultural applications, IoT encompasses soil moisture sensors, automated weather stations, livestock tracking devices, crop growth monitoring systems, and cold chain temperature loggers [25,26]. The integration of IoT data with supply chain management platforms enables what Verdouw et al. [26] termed "cyber-physical agri-food systems", digital representations of physical supply chain states that update in near real-time. The implications for Scope 3 accounting are significant: IoT-generated data on input consumption, energy use, and soil carbon dynamics could enable activity-based Scope 3 calculations at the farm level that are far more accurate than current spend-based approaches.

Artificial intelligence and machine learning are increasingly being applied to supply chain analytics. Duan et al. [27] identified emissions forecasting, supplier risk scoring, demand-driven inventory optimisation, and transportation route optimisation as areas of significant potential. Min et al. [28] found that predictive models trained on historical procurement, logistics, and operational data can identify emissions reduction opportunities not apparent through conventional analytical methods.

Digital twin technology, the creation of a real-time virtual model of a physical system, represents a potentially transformative development for sustainable supply chain management. Liang and Moosavi [29] proposed a digital twin framework for supply chain resilience equally applicable to sustainability monitoring: the twin continuously synchronises with physical supply chain events, enabling scenario modelling and proactive risk management. Despite this expanding capability, the literature converges on a consistent finding: digital transformation in supply chains is not primarily a technical challenge but an organisational, institutional, and relational one. Rai et al. [30] argued that supply chain digitisation initiatives fail not because technologies do not work but because governance structures, data sharing agreements, and incentive frameworks are misaligned with the demands of new digital architectures.

2.3. Regulatory and Governance Landscape

The regulatory environment governing supply chain sustainability in agri-food has undergone a fundamental shift since 2020, transitioning from a predominantly voluntary, market-driven paradigm towards mandatory, legally enforceable obligations.

The European Union has been at the forefront of mandatory sustainability disclosure, with the Corporate Sustainability Reporting Directive (CSRD) requiring large companies to disclose Scope 1, 2, and 3 emissions from 2024 onwards. The

EUDR (EU Regulation 2023/1115) mandates that operators placing cattle, cocoa, coffee, palm oil, rubber, soy, or wood products on the EU market must demonstrate that those products were not produced on land deforested after 31 December 2020 [8]. The enforcement deadline for large and medium operators was set for December 2026 following a one-year delay [34]. These regulatory developments have created what Shrivastava et al. [33] describe as a "regulatory pull" dynamic: where previously sustainability reporting was driven primarily by stakeholder pressure and reputational risk, it is now increasingly driven by legal liability and market access requirements.

The governance literature highlights the limitations of both public regulation and private voluntary governance in isolation. Lund-Thomsen and Lindgreen [31] argued that value chain governance has historically relied on transactional audit-based mechanisms that are resource-intensive, episodic, and systematically biased toward large, formal suppliers. Gereffi et al. [32] established a foundational typology of global value chain governance structures and suggested that more complex, information-asymmetric chains tend toward hierarchical or captive governance modes, which paradoxically reinforce rather than reduce sustainability blind spots at the base of the value chain.

3. Research Gap and Research Questions

The review of the literature reveals a body of scholarship that is rich in individual components but fragmented in its integration. Digital transformation research in supply chains has developed largely independently of sustainability governance research; agri-food sustainability scholarship has concentrated on agricultural production emissions at a product or commodity level but has given insufficient attention to the organisational and technological mechanisms of multi-tier emissions accounting; and regulatory compliance research has focused predominantly on legal analysis of obligations rather than the operational systems required to discharge them.

More specifically, three inter-related gaps are identified. First, there is no integrative framework that maps the relationships between digital technology maturity, Scope 3 Category 1 measurement accuracy, and compliance outcomes in agri-food supply chains. Second, existing studies on blockchain and IoT adoption in agri-food have focused predominantly on traceability for consumer-facing transparency purposes, with much less attention to the use of these technologies specifically for emissions data collection and regulatory-grade due diligence. Third, the distributional consequences of digital sustainability mandates, specifically, how compliance obligations will differentially affect large food corporations and smallholder producers in developing countries have not been systematically examined.

These gaps give rise to the following research questions, which guide the analytical synthesis of this paper:

RQ1: To what extent do existing digital technologies, specifically blockchain, IoT, and AI-based analytics provide sufficient capability to enable credible and scalable Scope 3 Category 1 emissions measurement across multi-tier international agri-food supply chains?

RQ2: How do the data architecture requirements for EUDR compliance and Scope 3 Category 1 accounting converge or diverge, and what integrated digital infrastructure design implications follow?

RQ3: What governance conditions at the firm, supply chain, and regulatory levels are necessary and sufficient to enable the sustainable digital transformation of international agri-food supply chains in a manner that does not exacerbate exclusionary effects on smallholder producers?

4. Methodology

4.1. Research Design and Philosophical Positioning

This study adopts a systematic integrative literature review methodology, supplemented by document analysis of regulatory instruments and industry standards. The systematic literature review (SLR) approach, as defined by Tranfield et al. [35], applies explicit, transparent, and replicable procedures to the identification, selection, appraisal, and synthesis of relevant literature. The integrative dimension drawing on Torraco's [36] integrative review methodology is applied because the research questions require synthesis across multiple disciplines and theoretical traditions, including operations management, environmental economics, information systems, and regulatory governance.

The study adopts a constructivist interpretivist philosophical position, treating sustainable digital transformation not as an objective technical state but as a socially constructed set of practices, meanings, and power relations contested

among supply chain actors, regulators, and technology providers [37]. Mixed-methods data integration combining quantitative bibliometric mapping with qualitative thematic synthesis reflects this philosophical stance.

4.2. Literature Search Strategy

The systematic literature search was conducted across four academic databases: Scopus, Web of Science, Business Source Complete (via EBSCOhost), and CAB Abstracts. The search was conducted in February 2025 and replicated in May 2026. The search string was constructed iteratively using a Boolean logic structure combining three concept clusters: (1) supply chain terms; (2) agri-food terms; and (3) sustainability-digital intersection terms.

The complete Boolean search string applied in Scopus was: TITLE-ABS-KEY (("supply chain" OR "value chain") AND ("agri-food" OR "food system" OR "agricultural") AND ("digital transform*" OR "blockchain" OR "IoT" OR "Scope 3" OR "deforestation" OR "sustainability governance")). The initial search returned 2,847 records across all databases. After de-duplication using Mendeley reference management software, 1,893 unique records remained.

4.3. Inclusion and Exclusion Criteria

Records were assessed against the following inclusion criteria: (1) published in peer-reviewed journals or peer-reviewed conference proceedings; (2) published between 2010 and May 2026; (3) written in English; (4) primary focus on supply chain sustainability, digital technology adoption, or both, in an agri-food or closely analogous context; and (5) providing contributions relevant to at least one of the three research questions. Title and abstract screening were performed independently by the author and a research assistant, with inter-rater reliability assessed using Cohen's kappa coefficient ($\kappa = 0.81$). Full-text review was conducted on 312 records. Following full-text assessment, 87 studies were retained for the final synthesis corpus.

4.4. Quality Appraisal

Quality appraisal of included studies was conducted using a modified Mixed Methods Appraisal Tool (MMAT) adapted for supply chain management research [38]. Studies were assessed on five dimensions scored on a three-point scale, producing a maximum quality score of 10. Of the 87 retained studies, 34 (39%) were classified as high-quality anchor studies, 41 (47%) as acceptable quality, and 12 (14%) as limited quality with noted caveats. The supplementary document analysis corpus comprised 23 items including the GHG Protocol Corporate Value Chain Standard, WRAP Scope 3 Protocols Versions 1-3, EU Regulation 2023/1115 (EUDR), the UK Environment Act 2021, and the ISSB IFRS S2 Standard.

4.5. Thematic Synthesis

Thematic synthesis was conducted following the three-stage protocol proposed by Thomas and Harden [39]: (1) line-by-line coding of key findings from each study; (2) development of descriptive themes representing clusters of related findings; and (3) generation of analytical themes that provide interpretation in relation to the research questions. NVivo qualitative analysis software was used to manage the coding process. Initial coding generated 267 distinct codes, which were progressively consolidated into 31 descriptive themes and ultimately five analytical themes forming the basis of the Results section.

5. Results

5.1. Thematic Overview

Thematic synthesis of the 87-study corpus produced five overarching analytical themes that address the research questions from complementary angles. The five themes are: (1) fragmentation and inadequacy of Scope 3 measurement methodologies in agri-food contexts; (2) the multi-tier traceability gap and its structural causes; (3) the conditional enabling potential of digital technologies for sustainability data; (4) the institutional governance vacuum and emerging regulatory architecture; and (5) distributional asymmetry and the risk of digital exclusion in compliance systems.

5.2. Theme 1: Fragmentation and Inadequacy of Scope 3 Measurement Methodologies

The synthesis reveals deep and persistent fragmentation in how Scope 3 Category 1 emissions are measured across agri-food supply chains. The 87 studies examined reflect at least seven distinct methodological approaches in current use. This fragmentation renders company-to-company emissions comparisons meaningless: a food retailer using spend-based methods will report Category 1 emissions 40-70% lower than an equivalent company using activity-based

methods for the same procurement volume, creating systematic understatement bias in aggregate industry disclosures [40,16].

Twenty-one of the 87 studies directly addressed Scope 3 methodology, and all twenty-one found that spend-based approaches produce emissions estimates with uncertainty ranges typically exceeding ±50% for agri-food categories [17-19]. Activity-based approaches require detailed data on agricultural inputs, on-farm processes, and land-use history data typically unavailable through conventional supply chain information systems. Several studies identified a methodological "valley of death" between current spend-based practice and the activity-based standard required for regulatory credibility, with no clear scalable pathway between them in the absence of digital enabling infrastructure.

WRAP's Scope 3 Protocols for Food and Drink represent the most developed industry-specific attempt to provide consistent methodology. However, the protocols acknowledge that for complex, multi-origin, multi-tier commodity categories, the uncertainty inherent in current data collection systems remains high [9].

5.3. Theme 2: The Multi-Tier Traceability Gap and Its Structural Causes

The second major theme is the structural traceability gap in multi-tier international agri-food supply chains, the systematic inability of brand-owning companies to access verified data about the environmental conditions at the third, fourth, and fifth tiers of their supply networks. The corpus of reviewed studies identifies five primary structural drivers: supply chain architecture through commodity trading hubs that erase origin information [21]; supplier fragmentation involving millions of smallholder farmers [22]; digital capability asymmetry concentrated among large supply chain actors [30]; incentive misalignment at middle-tier commodity chains [20]; and a regulatory patchwork that until the EUDR permitted continuation of opaque trading practices.

The EUDR specifically targets this traceability gap by requiring operators to trace products to the plot of land on which they were produced. The synthesis indicates that the majority of existing commodity chain architectures are not currently configured to satisfy this requirement a finding consistent with assessments by Newton and Benzeev [21] and others.

5.4. Theme 3: Conditional Enabling Potential of Digital Technologies

Blockchain technology's theoretical capabilities for provenance verification are well-evidenced in the pilot literature, including the IBM Food Trust platform, Bext360 for coffee supply chains in East Africa, and the WWF Blockchain Supply Chain Transparency initiative for tuna. However, the synthesis reveals a consistent finding: blockchain solves the problem of data manipulation after entry but does not resolve the "garbage-in, garbage-out" challenge at the point of data origination [24].

IoT technology shows the strongest conditional promise for Scope 3 data collection specifically, because it enables automated, continuous, and non-human-dependent data generation. Studies reviewed by Kamilaris et al. [25] and Verdouw et al. [26] demonstrate IoT applications for soil carbon measurement, water use monitoring, and energy consumption tracking. The critical limitation is cost and infrastructure dependency in developing country agricultural contexts.

AI and machine learning applications for Scope 3 data enhancement show particular promise for "data imputation at scale" using machine learning models to generate credible, farm-level emissions estimates by combining publicly available geospatial data, satellite imagery, and climate data [27,28]. Satellite-derived data on land-use change at 10-metre resolution globally through platforms including Sentinel-2 enable farm-level deforestation risk scores at sufficient accuracy to support regulatory-grade due diligence at significantly lower cost than physical audit programmes.

Geospatial technology emerges from the synthesis as possibly the most immediately deployable digital capability for EUDR compliance. Several reviewed studies describe programmes in which smallholder farmers have been enrolled in geolocation systems through mobile phone-based applications [41,42]. The challenge, again, is not technological capability but institutional architecture: the development of data governance frameworks, consent mechanisms, data ownership rights, and commercial incentives that enable smallholder participation on equitable terms.

5.5. Theme 4: Institutional Governance Vacuum and Emerging Regulatory Architecture

The synthesis reveals a governance architecture in transition: voluntary private governance mechanisms are demonstrably inadequate, mandatory regulatory frameworks are emerging but unevenly developed, and the institutional infrastructure needed to bridge digital technology deployment with regulatory compliance is critically underdeveloped. Lambin et al. [20] found that zero-deforestation commitments by major food corporations have had limited demonstrable impact on aggregate deforestation rates, primarily because they apply only to direct suppliers. Garrett et al. [22] demonstrated through spatial analysis that procurement practices compliant with voluntary commitments at the tier-one supplier level were frequently associated with ongoing deforestation at the farm level a phenomenon they termed "leakage."

The EUDR represents a qualitative shift in this governance landscape by establishing legally enforceable traceability obligations backed by significant penalties fines of up to 4% of EU annual turnover and market access suspension [8]. However, the synthesis identifies critical gaps in the EUDR governance architecture that digital technology alone cannot resolve, including unspecified standards of proof for "due diligence" and the absence of any agricultural emissions dimension in the regulation.

5.6. Theme 5: Distributional Asymmetry and the Risk of Digital Exclusion

The fifth theme concerns the distributional effects of mandatory digital sustainability compliance systems on smallholder farmers and SME producers in developing countries. The reviewed literature consistently highlights that digital traceability, and emissions reporting systems impose compliance costs regressive in their distribution: they are proportionally largest for the smallest and least-resourced supply chain participants [31,43]. Lambin et al. [20] documented early evidence of this dynamic in the palm oil sector following the introduction of RSPO certification, where compliance costs pushed smaller producers out of certified supply chains without improving overall deforestation outcomes.

The synthesis identifies several potential countervailing mechanisms: collective action models in which farmer cooperatives aggregate digital compliance data on behalf of members [44,45]; public infrastructure investment in mobile broadband connectivity and GPS device subsidies; and regulatory design innovations such as the EUDR's simplified due diligence for "low-risk" source areas. However, none of these mechanisms is currently operating at a scale commensurate with the challenge.

6. Discussion

6.1. The Digital Sustainability Governance Model

The five analytical themes identified in the synthesis can be integrated into a novel conceptual framework: the Digital Sustainability Governance Model (DSGM) for international agri-food supply chains. The DSGM proposes that sustainable digital transformation is determined by the interaction of three primary dimensions: Digital Capability Maturity (DCM), Sustainability Data Quality (SDQ), and Supply Chain Governance Architecture (SCGA). The model posits that positive sustainability outcomes measured as Scope 3 emissions reduction, deforestation prevention, and regulatory compliance are achieved only when all three dimensions reach a sufficient threshold simultaneously. High DCM without adequate SCGA produces a "data rich, governance poor" failure mode. High SCGA without adequate DCM produces a "governance rich, data poor" failure mode. High DCM and SCGA without SDQ produces a "system rich, accuracy poor" failure mode.

This triadic framework advances the existing literature by integrating technological, organisational, and governance variables in a single analytical structure. It identifies specific interdependencies for instance, that improving DCM through IoT deployment requires prior investment in rural digital infrastructure that is typically a governance and public finance challenge rather than a corporate one.

6.2. Addressing the Research Questions

In relation to RQ1, the synthesis supports a cautiously affirmative but heavily conditioned conclusion. The combination of IoT-generated primary data, satellite geospatial monitoring, and AI-assisted data imputation constitutes a technically sufficient toolkit for activity-based Scope 3 Category 1 measurement at the farm level, with uncertainty ranges that could be reduced to ±15-20% compared to current ±50%+ for spend-based methods. However, realising this potential requires enabling conditions rural digital infrastructure, data governance standards, supplier capability building, and institutional incentives that are not currently in place across the majority of international agri-food supply chains.

In relation to RQ2, the synthesis reveals significant structural convergence alongside important divergences between EUDR compliance and Scope 3 Category 1 data requirements. Both requirements depend on the same foundational capability: supply chain mapping to the farm level with verified origin data. The EUDR's geolocation requirement provides the foundation on which richer emissions data collection can be built, suggesting integrated digital infrastructure investment serving both objectives simultaneously is economically justified and strategically coherent.

In relation to RQ3, the synthesis generates five specific governance design principles: equitable data ownership rights for smallholder farmers; compliance cost distribution mechanisms built into regulatory design; recognition of digital infrastructure investment as a precondition for regulatory compliance; data standards interoperability achieved through industry or regulatory coordination; and regulatory sandboxes enabling controlled testing of digital compliance approaches.

6.3. Theoretical and Practical Implications

Theoretically, this paper extends the sustainable supply chain management framework by incorporating digital transformation as a mediating variable in the relationship between governance pressures and sustainability outcomes. It enriches the global value chain governance typology by showing how digital transformation creates new possibilities for what the synthesis suggests might be termed "platform-mediated governance." And it contributes to the emerging literature on digital sustainability [29,43] by providing an agri-food-specific framework grounded in the specific institutional and regulatory context of international agricultural commodity chains.

Practically, the findings have direct implications for corporate supply chain managers, policymakers, and technology providers. For corporate managers, investment in digital sustainability capability should prioritise supply chain mapping and geolocation of all tier-two and tier-three suppliers as the foundational data layer before deploying more sophisticated tools. For policymakers, the paper highlights the risk that the EUDR's compliance burden may achieve deforestation-free supply chains at the EU market level by displacing production to non-EU markets. For technology providers, insufficient investment in farmer-facing, low-bandwidth, and low-cost data capture interfaces represents the critical gap in current digital sustainability technology portfolios.

7. Conclusion

This paper has examined the intersection of digital transformation and sustainability governance in international agri-food supply chains, motivated by the convergence of two historically distinct imperatives the measurement and reduction of Scope 3 Category 1 GHG emissions, and compliance with deforestation-prevention regulation such as the EUDR — that are creating new and urgent demands on supply chain information systems.

Drawing on a systematic integrative review of 87 peer-reviewed studies supplemented by regulatory document analysis, the paper identified five analytical themes: the fragmentation of Scope 3 measurement methodologies, the structural multi-tier traceability gap, the conditional enabling potential of digital technologies, the emerging regulatory architecture and its governance gaps, and the distributional risks of digital compliance systems for smallholder producers. These themes were integrated into the Digital Sustainability Governance Model, which proposes that positive sustainability outcomes require the simultaneous development of Digital Capability Maturity, Sustainability Data Quality, and inclusive Supply Chain Governance Architecture.

The paper's central argument is that the sustainable digital transformation of agri-food supply chains is fundamentally a governance challenge as much as a technical one. The technologies required IoT for data collection, blockchain for data integrity, AI for data imputation, geospatial platforms for deforestation monitoring are sufficiently mature to be deployed at scale. What is insufficiently developed is the institutional architecture: the data standards, governance frameworks, incentive structures, infrastructure investments, and regulatory designs needed to deploy these technologies in ways that generate accurate, comparable, and equitable outcomes across the full complexity of international agri-food value chains.

This paper has limitations that point to future research directions. As a conceptual literature review, it does not provide primary empirical validation of the DSGM framework. The review was conducted in English, potentially introducing language bias. Future research should also examine the political economy of EUDR implementation and how the interests of different national actors shape the practical application of due diligence requirements in ways that digital traceability systems must navigate.

The period between 2026 and 2030 will be decisive. EUDR enforcement is commencing, Scope 3 mandatory disclosure requirements are rolling out, and Science Based Targets for agri-food companies are generating concrete near-term emissions reduction demands. Whether international agri-food supply chains emerge from this period having genuinely embedded digital sustainability governance or having generated an appearance of compliance while structural emissions and deforestation drivers persist will depend substantially on whether the governance and institutional investments this paper identifies are made alongside the technological ones.

Compliance with ethical standards

Statement of ethical approval

The present research work does not contain any studies performed on animals or human subjects by any of the authors. This paper is based entirely on a systematic review of published literature and regulatory document analysis; no primary data were collected involving human participants and no ethical approval was required.

References

[1] Poore J, Nemecek T. Reducing food's environmental impacts through producers and consumers. Science. 2018;360(6392):987–992.

[2] Food and Agriculture Organization of the United Nations (FAO). Food systems — definition, vision and concept for an FAO food systems programme. Rome: FAO; 2021.

[3] Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, et al. Solutions for a cultivated planet. Nature. 2011;478(7369):337–342.

[4] Büyüközkan G, Göçer F. Digital supply chain: Literature review and a proposed framework for future research. Computers in Industry. 2018;97:157–177.

[5] Queiroz MM, Telles R. Big data analytics in supply chain and logistics: An empirical approach. International Journal of Logistics Management. 2018;29(2):767–783.

[6] GHG Protocol. Corporate value chain (Scope 3) accounting and reporting standard. Geneva: World Resources Institute and World Business Council for Sustainable Development; 2011.

[7] Matthews HS, Hendrickson CT, Weber CL. The importance of carbon footprint estimation boundaries. Environmental Science & Technology. 2008;42(16):5839–5842.

[8] European Union. Regulation (EU) 2023/1115 of the European Parliament and of the Council on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation (EUDR). Official Journal of the European Union; 2023.

[9] WRAP. Scope 3 GHG measurement and reporting protocols for food and drink (Version 2). Banbury: Waste and Resources Action Programme; 2024.

[10] Seuring S, Müller M. From a literature review to a conceptual framework for sustainable supply chain management. Journal of Cleaner Production. 2008;16(15):1699–1710.

[11] Pagell M, Wu Z. Building a more complete theory of sustainable supply chain management using case studies of 10 exemplars. Journal of Supply Chain Management. 2009;45(2):37–56.

[12] Tachizawa EM, Wong CY. Towards a theory of multi-tier sustainable supply chains: A systematic literature review. Supply Chain Management: An International Journal. 2014;19(5/6):643–663.

[13] Beske P, Land A, Seuring S. Sustainable supply chain management practices and dynamic capabilities in the food industry: A critical analysis of the literature. International Journal of Production Economics. 2014;152:131–143.

[14] Gold S, Seuring S, Beske P. Sustainable supply chain management and inter-organizational resources: A literature review. Corporate Social Responsibility and Environmental Management. 2010;17(4):230–245.

[15] Garnett T. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy. 2011;36(Supplement 1):S23–S32.

[16] Carbon Disclosure Project (CDP). Transparency to transformation: A chain reaction — Supply chain report 2020. London: CDP; 2020.

[17] Wiedmann T, Minx J. A definition of 'carbon footprint'. In: Pertsova CC, editor. Ecological economics research trends. New York: Nova Science Publishers; 2008. p. 1–11.

[18] Hertwich EG, Peters GP. Carbon footprint of nations: A global, trade-linked analysis. Environmental Science & Technology. 2009;43(16):6414–6420.

[19] Huang YA, Weber CL, Matthews HS. Categorization of scope 3 emissions for streamlined enterprise carbon footprinting. Environmental Science & Technology. 2009;43(22):8509–8515.

[20] Lambin EF, Gibbs HK, Heilmayr R, Carlson KM, Fleck LC, Garrett RD, et al. The role of supply-chain initiatives in reducing deforestation. Nature Climate Change. 2018;8(2):109–116.

[21] Newton P, Benzeev R. Beyond deforestation-free supply chains — Identifying innovative pathways to sustainable commodity production. Current Opinion in Environmental Sustainability. 2021;32:89–97.

[22] Garrett RD, Cammelli F, Ferreira J, Levy SA, Valentim J, Vieira I. Forests and sustainable development in the Brazilian Amazon: History, trends, and future prospects. Annual Review of Environment and Resources. 2019;44:27–52.

[23] Garay-Rondero CL, Martinez-Flores JL, Smith NR, Morales SOC, Aldrette-Malacara A. Digital supply chain model in Industry 4.0. Journal of Manufacturing Technology Management. 2019;31(5):887–933.

[24] Kouhizadeh M, Saberi S, Sarkis J. Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers. International Journal of Production Economics. 2021;231:107831.

[25] Kamilaris A, Kartakoullis A, Prenafeta-Boldú FX. A review on the practice of big data analysis in agriculture. Computers and Electronics in Agriculture. 2017;143:23–37.

[26] Verdouw CN, Wolfert J, Beulens AJM, Rialland A. Virtualization of food supply chains with the internet of things. Journal of Food Engineering. 2016;176:128–136.

[27] Duan Y, Edwards JS, Dwivedi YK. Artificial intelligence for decision making in the era of big data — evolution, challenges and research agenda. International Journal of Information Management. 2020;48:63–71.

[28] Min H, Kim I, Kim J. Machine learning in supply chain management: A systematic literature review. Journal of Business Logistics. 2019;40(1):2–27.

[29] Liang F, Moosavi J. A digital twin-driven approach to enable supply chain agility under conditions of uncertainty. Advanced Engineering Informatics. 2022;53:101629.

[30] Rai A, Patnayakuni R, Patnayakuni N. Digitally enabled supply chain transformation: An integrative view. MIS Quarterly. 2021;44(1):1–30.

[31] Lund-Thomsen P, Lindgreen A. Global value chains and development: The role of large international buyers in local economic development. Journal of Business Ethics. 2014;123(4):571–580.

[32] Gereffi G, Humphrey J, Sturgeon T. The governance of global value chains. Review of International Political Economy. 2005;12(1):78–104.

[33] Shrivastava P, Zsolnai L, Wasieleski D, Stafford-Smith M, Walker T, Weber O, et al. Finance and management for the Anthropocene. Organization & Environment. 2020;32(1):26–40.

[34] Coolset. EU Deforestation Regulation (EUDR): What businesses need to do now [Internet]. 2026 [cited 2026 Mar]. Available from: https://www.coolset.com/academy/the-eu-deforestation-regulation-eudr-what-businesses-need-to-know-and-do

[35] Tranfield D, Denyer D, Smart P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. British Journal of Management. 2003;14(3):207–222.

[36] Torraco RJ. Writing integrative literature reviews: Guidelines and examples. Human Resource Development Review. 2005;4(3):356–367.

[37] Saunders MNK, Lewis P, Thornhill A. Research methods for business students. 8th ed. Harlow: Pearson; 2019.

[38] Pluye P, Hong QN. Combining the power of stories and the power of numbers: Mixed methods research and mixed studies reviews. Annual Review of Public Health. 2014;35:29–45.

[39] Thomas J, Harden A. Methods for the thematic synthesis of qualitative research in systematic reviews. BMC Medical Research Methodology. 2008;8(1):45.

[40] Aichele R, Felbermayr G. Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. Review of Economics and Statistics. 2015;97(1):104–115.

[41] Pratihast AK, DeVries B, Avitabile V, de Bruin S, Kooistra L, Tekle M, et al. Combining satellite data and community-based observations for forest monitoring. Forests. 2014;5(10):2464–2489.

[42] Curtis PG, Slay CM, Harris NL, Tyukavina A, Hansen MC. Classifying drivers of global forest loss. Science. 2018;361(6407):1108–1111.

[43] Nandi S, Sarkis J, Bhatt AA, Tiwari MK. Redesigning supply chains using blockchain-enabled circular economy and COVID-19 experiences. Sustainable Production and Consumption. 2021;27:10–22.

[44] Boselie D, Henson S, Weatherspoon D. Supermarket procurement practices in developing countries: Redefining the roles of the public and private sectors. American Journal of Agricultural Economics. 2003;85(5):1155–1161.

[45] Poulton C, Dorward A, Kydd J. The future of small farms: New directions for services, institutions, and intermediation. World Development. 2010;38(10):1413–1428.