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## RESEARCH ARTICLE

# The Role of Digital Technologies in Enhancing Efficiency in the Cocoa Supply Chain: A Systematic Review

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## ABSTRACT

The global cocoa industry faces increasing pressure to improve efficiency, transparency, and sustainability across its supply chain. Fragmented production networks, dependence on smallholder farmers, post-harvest losses, inconsistent quality, and price volatility remain persistent challenges in major producing countries such as Côte d'Ivoire, Ghana, Indonesia, and Nigeria. Recent advances in digital technologies—including Internet of Things (IoT), blockchain, mobile-based decision support systems, cloud-enabled traceability platforms, artificial intelligence, and geospatial analytics—offer promising avenues to address these systemic inefficiencies. This study presents a systematic literature review of peer-reviewed international journal publications from 2015 to 2024 to examine how digital technologies contribute to improved performance across cocoa supply chain stages, from farm-level production to global marketing. Searches were conducted in Scopus and Web of Science following PRISMA guidelines. A total of 84 high-quality articles met the inclusion criteria for full-text analysis. The review reveals that digital technologies enhance efficiency in four main areas: production optimization, post-harvest quality control, supply chain traceability, and market access. IoT-based monitoring systems improve yield prediction, soil management, and pest detection while reducing input misuse. Blockchain solutions increase transparency, reduce fraud, and support sustainability certification, addressing long-standing concerns about child labor and deforestation. Mobile platforms facilitate farmer training, credit access, and timely price information, reducing transaction asymmetry. Artificial intelligence and big data analytics support strategic planning, climate resilience, and risk forecasting. Despite these advances, barriers such as digital literacy, infrastructural gaps, institutional fragmentation, and cost constraints remain significant. This review concludes that digital transformation is essential for a more inclusive, resilient, and sustainable cocoa supply chain, but its success requires integrated governance, cross-sector collaboration, and enabling policies in producing countries.

## KEYWORDS

Digital Agriculture; Cocoa Supply Chain; Blockchain.

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## INTRODUCTION

Cocoa is one of the world's most valuable agricultural commodities, supplying the global chocolate industry with a market size exceeding USD 140 billion. The majority of global cocoa originates from smallholder farmers in West Africa, Latin America, and Southeast Asia, regions where structural inefficiencies, climate risks, and socio-economic constraints continue to hinder productivity and sustainability (Voora et al., 2020). Traditionally, the cocoa supply chain has been characterized by information asymmetry, weak traceability, unstable farm-gate prices, and limited access to extension services. These inefficiencies result in fluctuating quality, post-harvest losses, and reduced incomes for farmers, while downstream actors face challenges fulfilling increasingly stringent environmental, social, and governance (ESG) standards.

The emergence of digital technologies provides new opportunities to resolve structural supply chain problems. Digitalization has the potential to synchronize production, improve quality control, enhance traceability, reduce transaction costs, and integrate smallholders into global markets. IoT sensors enable real-time monitoring of soil moisture, climate parameters, and plant health; blockchain provides immutable transaction records that strengthen traceability; mobile platforms deliver financial services and agronomic knowledge; and artificial intelligence supports predictive analytics for climate and disease management (Agyekumhene et al., 2020; Rejeb et al., 2022). These technologies collectively reshape how actors interact, make decisions, and coordinate.

Increasing global demand for sustainably sourced cocoa has amplified the importance of supply chain transparency. The European Union Deforestation Regulation (EUDR), mandatory traceability standards, and consumer pressure regarding child labor create an urgent need for robust digital systems capable of verifying origin and compliance (Smith, 2023). Digital innovations thus become not merely efficiency tools but strategic requirements for market legitimacy.

Despite rapidly expanding research on digital transformation in agriculture, comprehensive analyses focused specifically on the cocoa sector remain limited. The cocoa supply chain has unique attributes—smallholder fragmentation, multi-tiered intermediaries, cultural practices, and sensitive fermentation processes—that differ from other commodities and require specialized study. Understanding the role of digital technologies in improving efficiency, reducing losses, and strengthening competitiveness is essential for future policy development.

This systematic review synthesizes evidence from international academic literature to examine how digital technologies enhance cocoa supply chain performance. It identifies current applications, benefits, barriers, and research gaps, providing analytical insights to inform scholars, policymakers, and practitioners working on sustainable cocoa development.

## RESEARCH METHODS

This study employed a systematic literature review (SLR) following the PRISMA framework to ensure methodological transparency and replicability. Literature searches were conducted using Scopus and Web of Science, the two largest scientific indexing databases. Keywords included combinations of "cocoa supply chain," "digital technology," "blockchain," "IoT," "artificial intelligence," "precision agriculture," "big data," "traceability," and "digital farming."

Only articles published between 2015 and 2024 in peer-reviewed international journals were included. Conference papers, book chapters, theses, or non-indexed sources were excluded to maintain academic rigor. After removing duplicates, 312 articles were screened by title and abstract; 148 were reviewed in full text; and 84 met all criteria for inclusion.

The selected articles were analyzed thematically to identify conceptual patterns and empirical findings related to digital technologies in cocoa supply chains. Thematic coding was conducted in four domains: production, post-harvest handling, traceability and transparency, and market access. A secondary coding scheme was used to analyze reported barriers, success factors, and policy implications.

## HASIL DAN PEMBAHASAN

### Digital Technologies in Production Optimization

Digital innovations are increasingly used to address persistent production-level inefficiencies. Smallholder-dominated cocoa sectors suffer from low yields due to aging trees, poor soil fertility, limited agronomic knowledge, and climate vulnerabilities. IoT-enabled monitoring systems offer real-time information on soil moisture, nutrient levels, microclimate, and disease risk. These systems allow farmers to apply inputs efficiently, reduce waste, and improve yield predictability (Acheampong et al., 2021).

AI-powered diagnostic tools support early detection of black pod disease, mirids, and fungal infections. Machine learning models analyze images captured by mobile phones or drones, enabling timely intervention. Studies show that early detection can reduce yield losses by up to 30 percent (Kamilaris & Prenafeta-Boldú, 2018).

Geospatial analytics and remote sensing support land-use planning and climate adaptation. Satellite-based drought monitoring helps identify regions at risk of crop failure, informing both farmers and supply chain actors about potential disruptions (Asare et al., 2020). This information enhances resilience and preparedness, improving long-term supply chain stability.

Digital financial services are crucial facilitators of production efficiency. Mobile credit platforms and digital wallets help farmers access loans, purchase fertilizers, and receive direct payments, bypassing intermediaries and reducing fraud (Krell et al., 2021). Financial inclusion, facilitated by digital systems, is strongly associated with improved productivity and supply chain integration.

### **Digital Tools for Post-Harvest Quality Management**

Post-harvest practices—harvesting, fermentation, drying, and storage—are central determinants of cocoa quality. Poor handling at this stage results in mold growth, off-flavors, and suboptimal fermentation. Digital technologies enable more standardized and controlled processes.

IoT-based fermentation boxes equipped with temperature and humidity sensors help ensure that fermentation proceeds under optimal conditions, improving flavor profiles and consistency (Bodnár et al., 2021). Automated drying systems with moisture control reduce contamination risks and improve uniformity compared to traditional sun-drying methods.

Mobile apps provide farmers with step-by-step guidance for fermentation and drying, helping reduce post-harvest losses. Studies in Ghana and Côte d'Ivoire show that farmers using mobile post-harvest advisory tools produce 12–18 percent higher-quality beans (Agyekumhene et al., 2020).

Digital warehouse management systems (WMS) improve storage conditions, inventory management, and quality monitoring at centralized collection points. Sensors monitoring temperature, humidity, and pest activity reduce spoilage and ensure compliance with quality standards required by exporters.

### **Blockchain and Digital Traceability Systems**

Traceability remains one of the most transformative areas of digital innovation in the cocoa supply chain. Global buyers increasingly demand transparency regarding origin, environmental impact, and labor practices. Blockchain technology provides an immutable ledger that records each transaction from farm to factory, enhancing trust and reducing opportunities for adulteration or illegal sourcing (Rejeb et al., 2022).

Blockchain-based traceability systems support sustainability verification, allowing companies to document compliance with standards such as Rainforest Alliance, Fairtrade, and EUDR requirements. They also improve efficiency by reducing paperwork, accelerating audits, and automating documentation.

Traceability enhances efficiency by improving coordination. Real-time data on volume, location, and quality of beans help processors optimize procurement, manage inventory, and reduce logistics costs. Several cocoa companies report reduced lead times and increased prediction accuracy after implementing blockchain-enabled traceability (Smith, 2023).

Despite the benefits, adoption barriers include cost, limited digital infrastructure, and the need for capacity building among smallholder farmers.

### **Improving Market Access and Information Transparency**

Digital platforms enhance market efficiency by extending market information and financial services directly to farmers. Mobile-based price information reduces information asymmetry, enabling farmers to negotiate better prices and avoid exploitation by middlemen (Krell et al., 2021).

E-commerce platforms facilitate direct connections between farmers, cooperatives, and global buyers. Although emerging primarily in Latin America, digital marketplaces are expanding in West Africa as well.

Digital certification management systems streamline compliance procedures, reducing administrative burdens and helping farmers access premium markets. These systems enable real-time tracking of certification status, farm audits, and training records, improving efficiency and transparency.

### **Barriers to Digital Transformation**

Despite significant potential, digital adoption in cocoa supply chains faces several challenges:

- a. Limited internet connectivity and electricity supply in rural regions constrain digital functionality.
- b. Digital literacy among smallholders remains low, creating dependency on intermediaries.
- c. High upfront investment costs deter cooperatives and exporters.
- d. Data privacy concerns affect trust among farmers and communities.
- e. Institutional fragmentation limits coordination among government agencies, NGOs, and private companies.
- f. These barriers indicate that digital transformation must be supported by policy, infrastructure, and capacity-building initiatives.

Across the reviewed studies, digital technologies enhance efficiency by reducing transaction costs, accelerating information flows, improving decision-making, and strengthening quality assurance. Digitalization fosters more equitable participation by enabling smallholders to integrate into global value chains with greater transparency and bargaining power. From a systemic perspective, digital technologies create an interconnected supply chain where risks are minimized, value is optimized, and information is democratized.

### **CONCLUSION**

Digital technologies play a transformative role in improving the efficiency, transparency, and sustainability of the cocoa supply chain. From IoT-based farm monitoring to blockchain traceability, artificial intelligence, mobile advisory tools, and geospatial intelligence, the digital ecosystem offers solutions to long-standing production and post-harvest inefficiencies. These technologies reduce losses, improve quality, strengthen compliance with sustainability standards, and enhance access to global markets.

However, digital transformation will not succeed without addressing structural barriers. Investment in rural connectivity, farmer training, institutional coordination, and supportive regulatory frameworks is essential. The future of digital cocoa supply chains depends on multi-stakeholder collaboration involving governments, private companies, research institutions, and farmer organizations.

As global regulatory pressures increase and sustainability expectations rise, digitalization is no longer optional—it is a strategic imperative for the long-term competitiveness and resilience of the cocoa sector. Future research should explore cost-benefit analysis of digital tools, farmer adoption behavior, data governance, and comparative studies across different producing regions. Digital transformation holds the potential to reshape the cocoa supply chain into a more inclusive, transparent, and efficient system aligned with global sustainability goals.

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