



Empowering smallholder farmers with blockchain-enabled digital identities: The case of CIMMYT for traceability, financial inclusion and value chain integration

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Abstract

This paper examines the transformative potential of blockchain-enabled digital identities in empowering smallholder farmers, with a specific focus on CIMMYT's initiatives in the Global South. By providing farmers with secure, verifiable credentials and data wallets, these technologies address critical challenges in financial inclusion, supply chain traceability, and data governance. Leveraging case studies from CIMMYT's partnerships with Blunumber and Identi, the paper explores the application of blockchain to enhance data ownership, improve market access, and foster transparency within agrifood systems. Findings highlight how digital identities enable farmers to control and monetize their data, access financial services, and comply with traceability standards, thereby strengthening their position in global value chains. Despite significant potential, challenges such as digital literacy gaps, infrastructure limitations, and regulatory disparities persist. The paper concludes with recommendations for scaling these solutions, emphasizing region-specific adaptations, collaborative frameworks, and robust data governance to maximize impact and inclusivity.

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Introduction

Smallholder farmers are central to global agricultural systems but often face barriers to accessing financial services, achieving traceability compliance, and adopting sustainable agricultural practices. Blockchain-enabled digital identities and data wallets, defined by the European Commission as applications that securely store, manage, and share personal identification data, credentials, and other relevant information, offer significant potential to empower farmers by providing control over their data. These tools enable smallholders to securely manage and share critical information, such as production practices and certification records, which facilitates access to financial services, compliance programs, and premium markets. By promoting transparency and traceability within the value chain, they strengthen farmers' bargaining power and foster equitable market integration.

This report examines these solutions through the case of CIMMYT (International Maize and Wheat Improvement Center), focusing on their application to financial inclusion, value chain traceability, and climate-smart agriculture. By connecting farmers with aggregators, buyers, financial institutions, and other stakeholders,

blockchain-enabled digital identities enhance transparency, compliance, and empowerment across the value chain.

Context and Background

Smallholder farmers, particularly in the Global South, are critical to food production and rural economies but face structural barriers that hinder their participation in formal agricultural markets. Challenges such as fragmented supply chains, limited market access, and a lack of data ownership exacerbate these inequities (FAO, 2021). Data fragmentation across disconnected systems controlled by intermediaries reduces transparency and perpetuates power imbalances (World Bank, 2018). Traditional systems also often restrict smallholders' ability to control and monetize their information, limiting their opportunities to negotiate better terms with buyers or access premium markets (Laroya et al., 2020; Tripoli & Schmidhuber, 2018).

Blockchain technology addresses these challenges by creating a decentralized, secure system for data management. Its immutable ledger allows all actors in the supply chain to access and verify data without reliance on central authorities (Antonucci et al., 2019; Quayson, 2020). Blockchain also ensures data transparency and builds trust among stakeholders, enabling smallholders to engage more effectively in formal markets (Kumarathunga, 2022).

Standardized digital identities further enhance smallholders' market access by offering verifiable credentials linked to blockchain-based data wallets. These tools allow farmers to store, manage, and share critical information, such as certification records and transaction histories, securely and selectively. By improving visibility and traceability across value chains, these technologies not only promote accountability but also enhance smallholders' ability to comply with

standards, access financial services, and secure better prices (LACChain, 2021; FAO & ITU, 2019).

Focusing on smallholder farmers in the Global South is essential for building sustainable food systems. These farmers produce a significant portion of the world's food supply and operate in ecologically diverse regions that are key to addressing global food security and climate challenges (Lowder et al., 2021). Empowering them with blockchain-enabled digital identities supports more resilient and inclusive food systems while addressing systemic inequities (CGIAR, 2021).

Objective and Scope

This report aims to provide a research-driven analysis of standardized digital identities and blockchain-based data wallets in agri-food systems, with a particular focus on smallholder farmers in the Global South. It documents CIMMYT's decade-long exploration and its three-year collaboration with Blunumber and Identi, two organizations dedicated to developing and implementing digital identity solutions for farmers. The analysis evaluates the feasibility, scalability, and impact of digital identities linked to blockchain technology, exploring their potential to empower smallholders, improve data governance, and enhance supply chain transparency.

The document is structured into six sections. Following this introduction, Section 2 presents the conceptual framework and literature review, encompassing digital identities, blockchain, and data wallets in agri-food systems. It also outlines a framework for smallholder empowerment through digital identities, alongside an exploration of agrifood value chains and regenerative agriculture as contexts for utilizing digital identity solutions. Regenerative agriculture emphasizes restoring soil health, biodiversity, and ecosystem functionality while improving productivity

and profitability (LaCanne & Lundgren, 2018). Practices such as agroforestry, conservation tillage, and crop diversification enhance sustainability by rebuilding organic matter, increasing water retention, and mitigating climate change impacts. For smallholders, particularly in ecologically sensitive regions, regenerative agriculture offers pathways to sustainability through improved food security, resilience to environmental stressors, and economic viability (Mango et al., 2017; Cordova et al., 2018). These approaches align with ecological principles, reduce dependency on chemical inputs, and promote carbon sequestration (Villat et al., 2024). By requiring lower capital investment and leveraging local knowledge, regenerative practices also strengthen long-term productivity (Brown et al., 2017; Tessema et al., 2015; Nkala et al., 2011).

Section 3 details the case study methodology, including data sources, collection techniques, and qualitative analysis used to assess CIMMYT's work on digital identities for farmers. Section 4 examines the CIMMYT case study, with a focus on the technical and governance aspects of implementing digital identities and data wallets, offering insights and lessons learned. Section 5 synthesizes the benefits and challenges of blockchain-enabled digital identities, particularly in enhancing data ownership, financial access, and privacy. Finally, Section 6 concludes with a summary of key findings, providing recommendations for stakeholders and suggesting directions for future research to scale digital identity solutions globally.

Research Questions

The main research questions guiding this report are as follows:

1. Why blockchain and data wallets for smallholder farmers?

What are the benefits and challenges of implementing standardized digital identities with blockchain-based data wallets in agri-food systems, and what are

the comparative advantages of blockchain and data wallets for smallholder farmers compared to alternative digital identity solutions?

2. How do these technologies improve financial access, traceability, and compliance?

What specific challenges arise in terms of privacy, data governance, and technological infrastructure?

3. What lessons can be drawn from CIMMYT's approach to addressing scalability challenges in implementing digital identity solutions for smallholder farmers?

How do regional differences across Africa, Asia, and Latin America impact the infrastructure, data governance, and implementation of digital identity and blockchain technologies? What regional adaptations are necessary to address disparities in digital literacy, regulatory environments, and infrastructure readiness?

4. Do blockchain-enabled digital identities influence data sovereignty and governance for smallholder farmers?

Blockchain-enabled digital identities can enhance data sovereignty for smallholder farmers by allowing them to own, control, and decide how their data is shared and used, reducing reliance on intermediaries. These systems have potential to improve governance by promoting transparency, accountability, and trust within agricultural value chains through immutable and verifiable data records.

Conceptual Framework and Literature Review

Digital Identities and Blockchain

Digital identities provide smallholder farmers with secure, verifiable credentials, enabling their participation in formal markets. Blockchain technology enhances

this system by offering immutable, tamper-proof records, ensuring transparency and trust across the value chain. Data wallets, an extension of digital identities, allow farmers to store and share key information, such as certification records, production practices, and financial histories, facilitating market access and compliance (FAO, 2021; IFAD, 2019; World Bank, 2018).

The growing complexity of global agri-food systems, particularly in the Global South, necessitates innovative solutions to enhance transparency, inclusivity, and efficiency. Smallholder farmers, who contribute significantly to food production, face barriers such as fragmented supply chains, limited digital tools, and lack of data control. The integration of blockchain technology and data wallets with standardized digital identities offers a transformative approach, empowering farmers to own, manage, and monetize their data (Daniel & Speranza, 2020; LACChain, 2021; Van Wassenaeer et al., 2021).

Defining Key Concepts

A trusted digital identity is essential for smallholder farmers to establish credibility within agri-food systems. Verified digital identities enable engagement with formal supply chains, access to financial services, and validation of producer status, prerequisites for higher-value market participation (World Bank, 2018). These trusted identities reduce fraud risks and facilitate reliable transactions, fostering stronger relationships between farmers, buyers, and financial institutions (WEF, 2020).

Decentralized Identity Systems: Unlike traditional systems managed by central authorities, decentralized identity systems grant farmers control over their data. Verified by trusted entities, these systems enhance data reliability and security while safeguarding farmer autonomy (López &

Cerón, 2021). Farmers can selectively share credentials, ensuring privacy and trust within complex supply chains.

Standards and Interoperability: Interoperability ensures that digital identities function seamlessly across platforms and regions, enabling cross-border transactions. Standards such as W3C's decentralized identifiers (DIDs) support multi-platform recognition, allowing smallholders to access broader markets without requiring separate credentials (ITU, 2018; LACChain, 2021).

Privacy and Data Security: Privacy concerns are paramount for smallholder farmers, whose digital identities often contain sensitive personal and production data. Effective systems limit on-chain data to essential information, ensuring compliance with regulations such as GDPR. These safeguards encourage adoption by providing farmers with assurance that their data remains secure (WEF, 2020).

Digital Passports and Data Wallets: Standardized digital identities act as "digital passports," simplifying interactions within the agri-food ecosystem. Farmers can secure loans, obtain certifications, and engage in formal markets more efficiently (World Bank, 2018). Data wallets enable farmers to treat their data as an economic asset, selectively sharing it with buyers or certification bodies, and accessing tailored services and financial incentives (Bluenumber, 2023).

Blockchain and Agri-Food Systems: Blockchain's decentralized ledger technology ensures data integrity, transparency, and traceability, making it particularly beneficial for smallholder farmers. It supports food safety, reduces fraud, and facilitates compliance with certification schemes, enhancing market access (Tripoli & Schmidhuber, 2018; FAO & ITU, 2019).

Case studies, such as blockchain-enabled traceability in Vietnam's pork industry (Pham et al., 2022) and Honduras' coffee sector (Melo-Velasco et al., 2024), demonstrate its potential for improving traceability but highlight challenges like limited infrastructure and low participation rates.

Despite its advantages, blockchain implementation faces hurdles. Scalability remains a key issue, with current networks struggling to handle large transaction volumes efficiently, particularly in regions with limited digital infrastructure. High deployment costs and fragmented regulatory frameworks further impede adoption (FAO & ITU, 2019; Tyagi, 2023). Addressing these barriers requires targeted investments in infrastructure, capacity building, and harmonized policies.

Digital Identity Empowerment Framework

The European Digital Identity Architecture and Reference Framework (EU, 2022) offers a comprehensive approach to designing secure and interoperable digital identity systems. Aimed at facilitating seamless access to public services across borders, the framework assigns specific roles to actors such as end users, wallet issuers, and trusted registry providers, each responsible for maintaining identity security and fostering trust. Functional requirements, including cryptographic verification, mutual authentication, secure storage, and electronic signatures, ensure robust security and user autonomy. Non-functional requirements, such as scalability, interoperability, and alignment with GDPR, further enable compatibility across Member States while adhering to stringent data protection laws. With its modular structure, the framework provides adaptable components for implementing standardized digital identity systems across the European Union.

Although designed for the EU context, the EUDI framework provides transferable principles for developing secure, privacy-preserving digital identity systems in non-EU regions. Features such as decentralized identifiers (DIDs), cryptographic verification, and GDPR compliance can be adapted to address specific challenges in low-resource settings, including limited infrastructure and diverse regulatory environments. By adopting these principles, non-EU countries can develop interoperable digital identity solutions that facilitate cross-border trade, enhance data sovereignty, and integrate smallholder farmers into international markets. However, these solutions must address local needs, such as cost-effective implementation, offline functionality, and multilingual interfaces, to ensure inclusivity and practical applicability.

Global frameworks such as the World Economic Forum's report, *Reimagining Digital Identity: A Strategic Imperative* (WEF, 2018), and the ITU's *Digital Identity Roadmap Guide* (ITU, 2018), reinforce the importance of designing systems that are user-centric, interoperable, and secure. The WEF report emphasizes the transformative potential of digital identity as critical infrastructure for modern economies while cautioning against poorly implemented solutions that risk identity theft and privacy breaches. It advocates for collaborative governance and adherence to international standards to maximize benefits and safeguard user trust. Similarly, the ITU roadmap outlines a phased strategy for implementation, beginning with establishing core principles such as data protection and interoperability. It underscores the need for stakeholder collaboration, privacy safeguards, and phased rollouts to ensure scalability and sustainability over time. Together, these frameworks highlight the importance of addressing technical, social, and governance challenges to develop inclusive and robust digital identity systems.

Blockchain-enabled digital identities and data wallets align with these principles and offer transformative potential for smallholder farmers. By granting farmers ownership and control over their data, these systems address systemic inequities in the agri-food sector. Farmers can decide when, how, and with whom their data is shared, enabling them to negotiate better terms with buyers and service providers. Blockchain technology further ensures data immutability, creating a trusted digital environment that facilitates market participation and promotes accountability within supply chains (Gumbi et al., 2023; Tyagi, 2023). Verified digital identities allow smallholders to access financial services such as credit and insurance, while data wallets provide proof of compliance with certification standards, increasing eligibility for premium markets and improving economic stability (World Bank, 2018; Tyagi, 2023).

In addition to empowering individual farmers, blockchain's decentralized ledger enhances traceability across agri-food value chains. By capturing every transaction from production to distribution, it ensures transparency and accountability, supporting food safety and regulatory compliance. This fosters consumer confidence in product quality and strengthens the integrity of supply chains, enabling smallholders to participate more effectively in formal markets (Tripoli & Schmidhuber, 2018; Tyagi, 2023). Blockchain-enabled digital identities also facilitate responsible sourcing and environmental compliance, contributing to sustainable agricultural practices and aligning with global sustainability goals (Punia et al., 2024).

However, several challenges must be addressed to scale blockchain-enabled digital identities effectively. Scalability issues, particularly in regions with limited digital infrastructure, pose significant barriers. High implementation costs, including hardware, software, and capacity-building efforts, exacerbate these challenges, especially for resource-constrained smallholders. Regulatory

fragmentation further complicates interoperability and data governance, impeding the development of cohesive frameworks. Addressing these challenges requires targeted investments in digital literacy, infrastructure, and regulatory harmonization (CGIAR, 2021; OECD, 2023). Future research should prioritize the development of cross-platform interoperability, economic analysis of standardization costs, and alignment of trade laws and data protection protocols to ensure inclusive and scalable solutions (Tyagi, 2023).

Blockchain-enabled digital identities hold significant promise for creating equitable, sustainable, and transparent agri-food systems. They facilitate data governance by reducing fraud risks and protecting farmers' privacy and ownership rights. By enabling access to financial services, certifications, and premium markets, these tools open economic opportunities for marginalized groups, including women farmers. Moreover, blockchain's traceability mechanisms promote responsible sourcing and resource management, ensuring alignment with international sustainability standards while addressing the structural barriers that have historically excluded smallholders from formal markets.

Blockchain for Farmer Digital Identity in Sustainable Agri-Food Value Chains

The literature on blockchain and digital identities underscores their transformative potential to empower smallholder farmers through enhanced data ownership, market access, and supply chain transparency. Digital identities, particularly those embedded within self-sovereign identity (SSI) systems, enable farmers to control their data securely and access a range of services. Decentralized identifiers (DIDs) and verifiable credentials (VCs) are critical components of these systems, providing a secure and privacy-preserving foundation for digital identities (LACChain, 2021; World Bank, 2018).

Blockchain's tamper-proof ledger plays a pivotal role in promoting transparency within agri-food systems. By ensuring compliance with food safety standards and reducing fraud, blockchain provides a robust framework for trusted transactions in agriculture. For smallholder farmers, who often face barriers to demonstrating compliance, blockchain-enabled digital identities offer a pathway to formal market participation, financial services, and quality assurance programs. These innovations also promote rural economic development by empowering marginalized groups, including women farmers, who are frequently excluded from such opportunities (World Bank, 2018; Tyagi, 2023).

Despite their potential, regional disparities in infrastructure, regulatory environments, and socio-economic conditions significantly influence the adoption of blockchain-based digital identities. Limited digital literacy and technological infrastructure in some regions create additional hurdles. Studies emphasize the need for targeted investments to address these challenges, highlighting infrastructure development, capacity building, and education as critical to enabling technology adoption (CGIAR, 2021; OECD, 2023; UNDP, 2024). Nevertheless, blockchain-based digital identities also facilitate sustainable practices by ensuring traceability and environmental compliance. Blockchain's capacity to support responsible sourcing and food safety fosters consumer trust, which is crucial for building resilient and transparent supply chains (C.S., Vidhya et al., 2024; Sharma et al., 2024; FAO & ITU, 2019).

Standardization and interoperability are essential for the success of blockchain-enabled digital identity systems in agriculture. The adoption of global standards, collaborative governance models, and consortia-driven approaches can create integrated systems that enhance transparency, data ownership, and economic opportunities for farmers. Achieving this integration will require both technical advancements and policy alignment to ensure scalability and sustainability across

diverse regions. Such efforts are critical for fostering inclusive and effective agri-food systems that benefit all stakeholders.

Several studies illustrate blockchain's practical applications in enhancing food supply chains. Dock.io (2024) highlights blockchain's ability to improve transparency, traceability, and accountability, which are vital for combating food fraud and ensuring food safety. The immutable records provided by blockchain foster trust among stakeholders and enhance the efficiency of value chains (George & Al-Ansari, 2023). Similarly, Pham et al. (2022) examine blockchain-enabled traceability in Vietnam's pork industry, demonstrating its advantages in improving food safety and sustainability. The study shows how blockchain can empower stakeholders by providing transparent records of product origin, though it also notes challenges such as infrastructure limitations and inconsistencies in data formats. These findings underscore the importance of developing standardized data protocols and interoperability to facilitate seamless cross-platform integration.

Another study by Roopa et al. (2022) introduces "Agro-Chain," a blockchain-powered platform designed to provide micro-financial assistance to farmers. This initiative highlights blockchain's potential to enhance financial inclusion by enabling access to decentralized financing options. The transparent and secure nature of blockchain-supported systems fosters smallholder engagement in formal financial systems, contributing to economic resilience in rural communities.

While there has been progress in standardization and interoperability, further research is needed to develop scalable solutions tailored to diverse regional contexts. Cross-platform interoperability, economic analyses of standardization costs, and the alignment of trade laws, data protection standards, and verification protocols are critical areas for future research. Addressing these challenges will

enable the creation of cohesive frameworks that support interoperability, foster trust, and maximize the benefits of blockchain-enabled digital identities in agriculture (Tyagi, 2023).

CIMMYT Case Study: Blockchain-Enabled Digital Identities and Regenerative Agriculture

CIMMYT has pioneered a data-driven approach to regenerative agriculture, leveraging over a decade of farmer-centered data collection and analysis across multiple countries. The organization's efforts have focused on addressing critical challenges such as soil degradation, biodiversity loss, declining agricultural productivity, and the need for sustainable farming practices. Through the integration of agronomic data, digital tools, and blockchain-enabled systems, CIMMYT has worked to empower farmers, enhance sustainability, and promote the adoption of regenerative agricultural practices.

Regenerative agriculture addresses key components of agroecosystems, including soil health, water efficiency, air quality, profitability, and biodiversity. CIMMYT has implemented strategies to improve organic carbon levels, aggregate stability, water infiltration rates, greenhouse gas emissions, and pollinator abundance while stabilizing yields and enhancing farmers' access to markets. These efforts span multiple regions, including Latin America, South Asia, and Africa, and involve over 289,000 farmers managing more than 317,000 plots, collectively generating over 24 million data points. To support these efforts, CIMMYT developed the RegAg Data Management System, which since 2012 has iteratively evolved to collect, process, and analyze large-scale field data. This system integrates advanced technologies, including IoT devices, in-field sensors,

drones, satellites, and farmer logs, to provide tailored agronomic recommendations for farmers and actionable insights for researchers.

Building on this foundational work, CIMMYT recognized the potential of blockchain technology to further enhance data governance and empower farmers. By treating data as an asset, CIMMYT sought to provide farmers with tools to securely own and share their data with stakeholders such as buyers, financial institutions, and certification bodies. The introduction of blockchain-enabled digital identities and data wallets emerged as a natural progression to address these goals while fostering transparency, traceability, and inclusivity within agricultural systems.

In 2023, CIMMYT partnered with Bluenumber to pilot a blockchain-based system providing smallholder farmers with self-sovereign identities (SSIs). This initiative aligned with CIMMYT's broader objective of promoting sustainable practices and improving data transparency in agri-food systems. Through Bluenumber's platform, farmers were able to create digital identities linked to secure personal data vaults (PDVs), which allowed them to control their data, verify its accuracy, and share it with consent-based protocols. The pilot introduced a data marketplace known as the Bluechip Exchange (BCX), where farmers could monetize their data by engaging directly with certified buyers interested in sustainability metrics. The platform emphasized user control and privacy by retrieving metadata rather than extracting raw data, ensuring that farmers retained ownership of their information while still participating in transparent transactions.

The Bluenumber-CIMMYT collaboration also highlighted the importance of regional adaptation and farmer engagement in the design and implementation of digital tools. Workshops held in regions such as Zacatecas and Guanajuato in Mexico provided hands-on training for farmers, introducing them to concepts of data ownership, digital identity creation, and the use of PDVs and marketplaces. These workshops also served as platforms for collecting user feedback, which informed iterative refinements to the platform. For example, simplifications in the registration process and enhancements to parcel mapping features addressed challenges raised by farmers, particularly those with limited digital literacy. However, the pilot faced persistent challenges, including low smartphone compatibility and limited internet access in rural areas, which necessitated further development of offline-compatible features and asynchronous data-sharing mechanisms.

In parallel, CIMMYT collaborated with Identi on a blockchain-enabled digital identity system as part of the e-Agrology platform. This initiative focused on enhancing transparency, security, and traceability in maize and wheat supply chains while enabling farmers to access critical services such as financial products, certifications, and market opportunities. Identi employed a decentralized identifier (DID) system, compliant with W3C standards, to create tamper-proof digital identities anchored in blockchain. These identities were integrated with data wallets that allowed farmers to securely store and share verifiable credentials, including production practices and certification records. Identi prioritized usability by incorporating widely accessible tools like WhatsApp and SMS, ensuring that the system could accommodate rural farmers with limited access to high-speed internet.

The Identi initiative also adopted an adaptive learning approach, incorporating interactive feedback from farmers and technicians to refine the digital identity tools. Workshops played a crucial role in demonstrating the practical benefits of these systems, such as linking certification data to improved market access. Farmer feedback highlighted initial difficulties with complex interfaces and plot data entry processes, leading to design adjustments that increased the system's relevance and usability. Additionally, Identi integrated the Mexican Unique Population Registry Code (CURP) into its platform, simplifying the identity verification process and aligning the system with established frameworks.

Despite their distinct approaches, both the Blunumber and Identi projects encountered similar challenges, including scalability, connectivity barriers, and digital literacy gaps. Introducing farmers to concepts such as blockchain, data sovereignty, and digital wallets required significant training and support, underscoring the importance of user-centric design and localized engagement. For instance, older farmers and those in communities with indigenous languages required additional resources to fully understand and adopt the technology. Economic barriers also emerged during the Blunumber pilot, where manual payment processing systems incurred high transaction fees, prompting the need for automated solutions to streamline incentive distribution.

The pilot projects revealed valuable lessons about the implementation of blockchain-enabled tools in agricultural systems. Building trust among farmers proved essential, particularly through transparent communication and the involvement of intermediaries such as local agricultural advisors. These trusted figures acted as bridges between the technology and the farmers, addressing concerns about data privacy and ensuring that the tools were culturally and contextually relevant. Furthermore, the iterative refinement of digital platforms

demonstrated the importance of incorporating farmer feedback into design processes to ensure alignment with their needs and preferences.

The integration of financial incentives through data marketplaces emerged as a powerful motivator for farmer participation. Farmers were particularly enthusiastic about the potential to monetize their data and access tailored services, such as certification benefits and market-based recommendations. However, scaling these systems will require addressing infrastructural limitations, such as expanding internet access in remote areas and developing cost-effective solutions for data governance and transaction management.

CIMMYT's experience with Blunumber and Identi underscores the transformative potential of blockchain technology in supporting financial inclusion, traceability, and sustainable practices. By treating data as an asset, these systems empower farmers while fostering transparency and efficiency across agricultural value chains. The incorporation of decentralized ecosystems like Agro Web 3, proposed by IFAD, further demonstrates the scalability and adaptability of blockchain-based solutions for addressing challenges such as data fragmentation and limited access to resources.

In conclusion, CIMMYT's case study highlights the critical role of institutional trust, regional adaptation, and collaborative partnerships in advancing digital innovation in agriculture. Blockchain-enabled digital identities represent a promising avenue for promoting inclusivity, enhancing data governance, and driving sustainability in smallholder farming systems. As CIMMYT continues to refine these technologies, its work serves as a model for leveraging decentralized systems to address global challenges in food security and environmental resilience.

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