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Block chain technology: A catalyst for transforming farmers' livelihoods in agriculture and allied activities

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Abstract

Agriculture is undergoing a major digital transformation, with blockchain technology emerging as a pivotal innovation. This review synthesizes evidence from 2015-2024 to examine how blockchain reshapes agri-food systems by improving transparency, traceability, and trust across supply chains. It highlights the integration of smart contracts, decentralized ledgers, and complementary digital tools (IoT, drones, sensors) that streamline transactions, reduce post-harvest losses, enable fairer compensation, and expand market access for farmers. Particular attention is given to the implications for smallholders, financial inclusion, and sustainable practices. By mapping benefits, barriers, and strategies for adoption, the paper underscores blockchain's potential to create an efficient, equitable, and climate-resilient agricultural ecosystem and to advance sustainable development goals in farming communities worldwide.

Keywords: Blockchain technology, Agriculture, Smart contracts, Supply chain transparency, Sustainable farming

Introduction

Agriculture represents a fundamental pillar of the global socio-economic structure, ensuring food security, providing livelihoods, and supplying raw materials for a wide array of industries. Its importance transcends simple food production, encompassing vital linkages with employment generation, rural development, and international trade (Pawlak & Kołodziejczak, 2020)^[43]. At present, the sector is undergoing revolutionary shifts propelled by state-of-the-art innovations that signal a new phase in agricultural practices. These advances not only improve efficiency and productivity but also confront critical issues such as resource limitations, climate change, and the urgent need for sustainable food systems (Zhang *et al.*, 2022)^[59]. In today's scenario, agriculture faces mounting food demand as a result of population growth, urbanization, and evolving dietary preferences. Within this context, technological progress plays an essential role in directly addressing these challenges (FAO, 2023). The incorporation of frontier technologies spanning precision agriculture, drone applications, artificial intelligence, and blockchain is empowering farmers with unmatched tools and insights (Gebresenbet *et al.*, 2023)^[10]. These advanced technologies not only enhance agricultural productivity but also strengthen sustainability by reducing environmental risks and encouraging prudent resource utilization (Christian *et al.*, 2024)^[12]. As the agricultural sector adopts such cutting-edge tools, it gains greater resilience, adaptability, and potential for sustained growth. The integration of technology with farming practices is creating a future in which agriculture can meet global food requirements while remaining environmentally responsible, economically sound, and socially inclusive (Pakseresht *et al.*, 2024)^[39]. The sweeping changes currently underway mark a turning point in the evolution of agriculture, with innovation emerging as a central driver of food security and the pursuit of a sustainable future for generations ahead (Robertson & Lapina, 2023)^[49].

Block chain technology is one of the cutting edge innovations in the recent years. The agricultural sector, is undergoing a transformative journey propelled by the integration of block chain technology (Awan *et al.*, 2021)^[7]. Originally recognized for its role in securing crypto currency transactions, block chain is now positioning itself as a revolutionary force with the potential to reshape the entire landscape of agriculture. This integration represents more than just a technological upgrade; it signifies a paradigm shift that is redefining traditional farming

practices and holds the promise of substantial benefits for farmers and stakeholders across the agricultural supply chain (Xiong *et al.*, 2020) ^[57]. Traditionally, agriculture has been fraught with challenges such as opacity in supply chains, inefficient transactions, and disparities in information access. Block chain technology, with its decentralized and tamper-resistant ledger system, emerges as a potent solution to address these issues (Panwar *et al.*, 2023) ^[42]. The transparency inherent in block chain ensures that every transaction and movement of agricultural goods is recorded in a secure, traceable, and verifiable manner. This not only reduces the risk of fraud but also empowers consumers with the ability to make informed choices about the origin, quality, and ethical considerations of the products they consume (Habib *et al.*, 2022) ^[25]. As the diverse effects of blockchain in agriculture are examined, it becomes clear that this technology has moved far beyond its initial uses, emerging as a catalyst for transformation across the sector. By increasing transparency and strengthening farmers' economic positions, blockchain is set to build a more resilient, efficient, and equitable agricultural landscape. This paper explores multiple facets of this integration, illustrating how blockchain is reshaping agricultural practices and advancing the sector's sustainable development (Friedman & Ormiston, 2022) ^[23].

Methodology

This study followed a structured, transparent, and reproducible literature-review process consistent with PRISMA guidelines. We designed the methodology to identify, select, and synthesise peer-reviewed and high-quality grey literature on blockchain applications in agriculture and their implications for farmers' livelihoods. The process comprised a systematic search strategy, predefined eligibility criteria, independent screening, data extraction, thematic synthesis, and quality assessment.

Search Strategy

A comprehensive literature search was conducted between January 2015 and August 2024 in five major databases: Scopus, Web of Science, AGRIS, PubMed, and Google Scholar. Search terms combined "blockchain" or "distributed ledger" with agricultural terms ("agriculture", "agri-food", "farmers", "supply chain") and "smart contract(s)" with "farmers", "finance", or "traceability". Boolean operators (AND/OR) and truncations expanded results. Reference lists of key articles and relevant grey literature were also hand-searched.

Eligibility Criteria

We included peer-reviewed journal articles, conference proceedings, and authoritative institutional reports published in English that

1. Explicitly examined blockchain or distributed ledger applications in agriculture or allied sectors;
2. Reported outcomes or implications for farmer livelihoods, supply-chain transparency, sustainability, or market access; or
3. Discussed implementation strategies and challenges.

We excluded studies that:

Focused solely on technical blockchain protocols without agricultural application; Dealt exclusively with cryptocurrencies; were non-English; were opinion pieces without empirical or conceptual contribution.

Data Extraction

Key variables were extracted into a standardized form:

publication year, study location, blockchain application (e.g., traceability, finance, smart contracts), combined technologies (IoT, drones, sensors), reported outcomes for farmers, barriers, and recommendations.

Synthesis

A thematic synthesis grouped findings under cross-cutting dimensions:

(i) Traceability & Transparency; (ii) Smart Contracts & Financial Inclusion; (iii) Sustainable Practices; (iv) Market Access; (v) Climate Resilience; (vi) Data Management; (vii) Community Empowerment; and (viii) Inclusion Strategies.

Quality Assessment

For empirical studies, quality was assessed using a modified Critical Appraisal Skills Programme (CASP) checklist adapted for technology interventions in agriculture. Conceptual papers were evaluated for clarity of framework and relevance.

PRISMA Flow

The search identified 450 records. After removing duplicates, 400 records remained. Screening titles/abstracts excluded 280. Full texts of 120 articles were assessed; 45 were excluded (not meeting eligibility), leaving 75 in the qualitative synthesis. After further appraisal, 60 studies were included in the final review

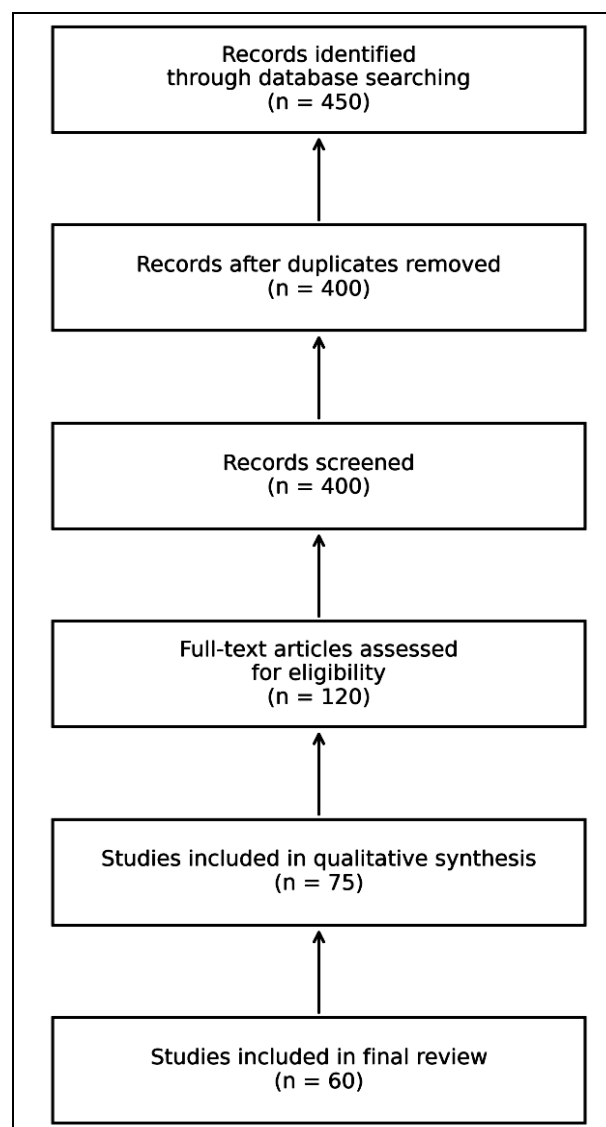


Fig 1: PRISMA style flow of Literature selection

Conceptual Background -What Blockchain Brings to Agriculture

Blockchain technology introduces a paradigm shift in how agricultural systems record, share, and verify information. At its core, blockchain provides three interrelated affordances that directly address long-standing inefficiencies in agri-food supply chains:

Transparency and Traceability

Blockchain's immutable, time-stamped ledger creates a verifiable record of every transaction and movement of goods along the value chain. For farmers, this means that inputs (such as seeds, fertilizers, and veterinary medicines) and outputs (such as harvested crops or livestock) can be tracked from origin to end consumer. For example, IBM Food Trust™ a blockchain platform used by Walmart and Carrefour allows producers to upload harvest data, enabling retailers and consumers to trace mangoes or leafy greens back to the farm within seconds rather than days. This level of transparency reduces fraud, strengthens food safety monitoring, and enhances farmers' reputations in premium markets.

Programmability via Smart Contracts

Smart contracts are automated, self-executing agreements embedded within a blockchain. They carry out pre-programmed actions once the specified conditions are fulfilled—for instance, releasing a payment when a shipment meets quality standards or arrives at a designated location. In the agricultural context, these contracts can streamline crop-insurance disbursements after verified weather events or enable farmers to receive immediate payment upon delivery rather than waiting for intermediaries (Ellahi *et al.*, 2023) [20]. Pilot initiatives in countries such as India and Kenya have demonstrated blockchain-based smart contracts delivering micro-insurance to smallholders affected by drought, thereby reducing administrative bottlenecks and transaction expenses. Furthermore, decentralized applications

(DApps) operating on blockchain can strengthen farmer cooperatives by facilitating collective resource management, knowledge exchange, and improved bargaining power with buyers (Merrell, 2022; Xiong *et al.*, 2020) [33, 57].

Decentralization and Trust Minimization

Traditional agricultural supply chains depend on a multitude of centralized intermediaries: traders, brokers, and certifying agencies to verify transactions. Blockchain minimizes this reliance by providing a shared, tamper-resistant ledger accessible to all authorized stakeholders. Farmers gain direct visibility into prices, buyers, and logistics, while buyers gain verifiable proof of origin, quality, and sustainability claims without relying solely on third-party attestations. This can level the playing field for smallholders, reducing information asymmetry and promoting fairer trade practices.

When combined with complementary digital technologies such as IoT devices (soil moisture sensors, GPS-enabled drones), geospatial mapping, and digital farmer identities, blockchain enables end-to-end digital records that extend from seed sourcing and on-farm practices through processing, distribution, and retail. For instance, in Ethiopia's coffee sector, blockchain pilots have linked farmers' digital IDs with GPS-stamped harvest data and quality scores, allowing roasters and consumers to directly reward producers for sustainable practices. Such integrations not only improve traceability and food safety but also support new business models, such as direct-to-consumer marketing, carbon credit verification, and cooperative profit-sharing. Taken together, these affordances transform blockchain from a mere technological add-on into a governance and empowerment mechanism for agriculture. By creating transparent, automated, and decentralized records, blockchain can foster greater accountability, trust, and efficiency across the agri-food system, ultimately improving farmer livelihoods and strengthening food system resilience.

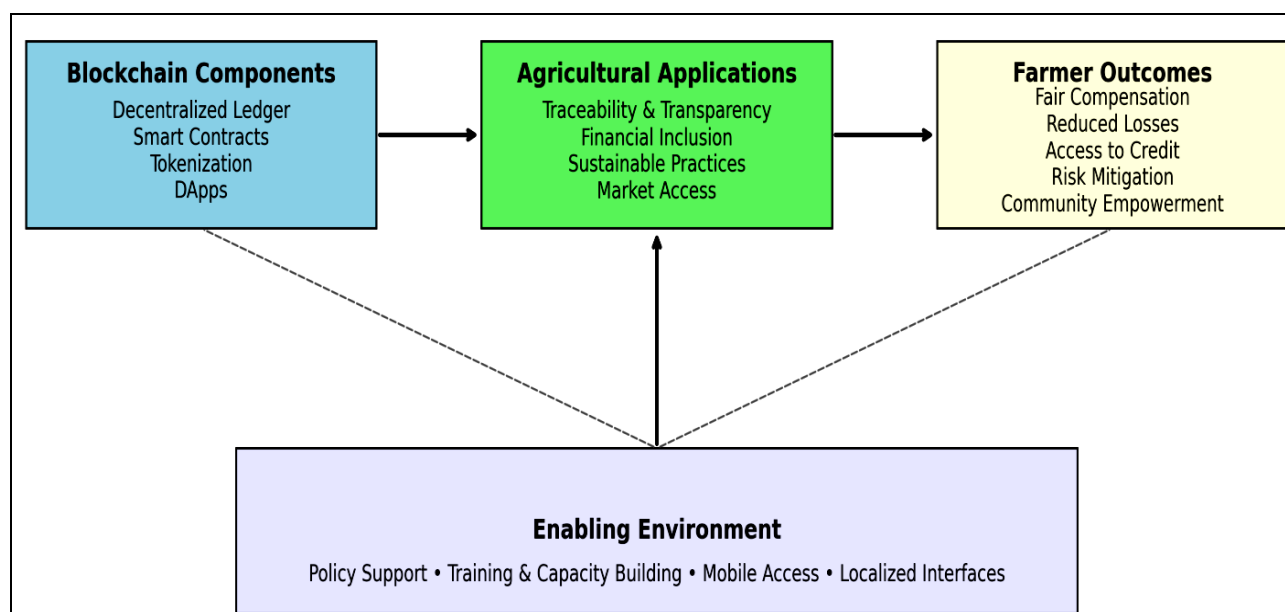


Fig 2: Conceptual Framework: Block chain Transforming Farmers' Livelihoods

Dimensions of technological integration of block chain in agriculture

Transforming Traceability and Transparency

A core aspect of blockchain's influence on agriculture is its capacity to transform traceability and transparency across the

entire supply chain. Traditionally, agricultural supply networks have struggled with information gaps and limited visibility (Agrawal *et al.*, 2021) [3]. Through its decentralized ledger, blockchain creates an unalterable and openly accessible record of each transaction from seed to shelf. This allows stakeholders

to follow the movement of agricultural goods with exceptional precision and provides consumers with details about product origins, farming methods, and ethical practices (Song *et al.*, 2023; Demestichas *et al.*, 2020) ^[32, 20]. By enhancing transparency in this way, blockchain helps curb fraud and equips consumers to make better-informed decisions, encouraging more responsible patterns of consumption.

Empowering Farmers through Smart Contracts

Block chain's integration into agriculture extends beyond supply chain transparency to empower farmers economically. The implementation of smart contracts, self-executing agreements with the terms of the contract directly written into code, is revolutionizing traditional farming transactions (Praveen *et al.*, 2021) ^[46]. Smart contracts automate and streamline processes such as payment for goods and services, providing farmers with secure and timely transactions (Taherdoost, 2023) ^[54]. This not only eliminates intermediaries but also opens up avenues for financial inclusivity, enabling farmers to access micro-financing and investment opportunities previously out of reach. In essence, block chain is not just a technological upgrade; it's a tool that is reshaping the financial landscape of agriculture, bringing economic empowerment to the forefront (Mhlanga, 2023) ^[34].

Market Access

A streamlined supply chain doesn't just bring efficiency; it opens up avenues for farmers to access markets on a broader scale. By minimizing logistical bottlenecks and reducing the complexities associated with traditional supply chains, block chain technology provides farmers with an expansive reach. This enhanced market access is transformative, allowing farmers to transcend geographic constraints and connect more efficiently with a diverse array of consumers and businesses (Jahanbin *et al.*, 2023) ^[26].

Through the removal of intermediaries and the adoption of transparent and automated transactions enabled by block chain, farmers can seamlessly navigate local and global markets, positioning themselves for increased sales opportunities and a more direct and equitable engagement with buyers. This expanded market reach not only augments their income potential but also amplifies their role in shaping market dynamics, contributing to a more inclusive and dynamic agricultural landscape (Rejeb *et al.*, 2020) ^[48]. As a result, the positive implications of block chain on market access ripple through the farming community, creating a ripple effect that fosters economic resilience and prosperity.

Facilitating Sustainable Practices

With sustainability taking centre stage globally, blockchain is emerging as a pivotal tool for promoting environmentally responsible farming practices. By supporting precision agriculture through data-driven decision-making, the technology helps optimise critical inputs such as water, fertilisers and pesticides (Abbasi *et al.*, 2022) ^[1]. Unmanned aerial vehicles (drones) integrated with blockchain systems can deliver real-time information on crop conditions, enabling earlier identification of pest or disease outbreaks. This targeted, optimised management cuts waste, lowers environmental impacts and advances the overarching objective of sustainable agriculture. Through the seamless convergence of digital technologies and farming activities, blockchain is driving a paradigm shift toward more accountable and sustainable production methods (Javaid *et al.*, 2023; Sharma *et al.*, 2023) ^[27, 51].

Financial Stability

Financial stability, a cornerstone of farmers' economic resilience, is a direct outcome of a well-organized and transparent supply chain. The intricate orchestration of the supply chain processes provides farmers with a dependable framework, enabling them to anticipate and secure a more predictable and stable income (Pera *et al.*, 2023) ^[45]. Through reliable and transparent transactions facilitated by block chain technology, financial uncertainties are mitigated, granting farmers the confidence to plan for the future with greater precision. This enhanced financial predictability transcends immediate monetary gains, empowering farmers to make strategic decisions about investments in agricultural practices, technology adoption, and infrastructure development (Dhanaraju *et al.*, 2022) ^[15].

Impact of blockchain on the livelihood of the farmers:

The positive impact of an efficient and transparent supply chain on the livelihoods of farmers in agriculture is multifaceted. Here are several key benefits:

1. Fair Compensation

Fair compensation is a crucial benefit in agricultural trade. An organized supply chain helps protect farmers from middlemen's undue influence, allowing them to get a larger share of the final product value (Kramer *et al.*, 2021) ^[30]. This enhances their economic well-being, provides financial stability for future planning, and encourages investment in sustainable practices. Fair compensation not only brings financial gains but also restores dignity and value to farmers, acknowledging their pivotal role in the agricultural supply chain (Abiri *et al.*, 2023; Alobid *et al.*, 2022) ^[2, 5].

2. Reduced Post-Harvest Losses

Reduced post-harvest losses stand as a pivotal advantage resulting from an optimized and transparent supply chain in the agricultural sector. The optimization of the supply chain is instrumental in mitigating delays that often accompany the transportation of agricultural products from farms to markets (Bustos & Moors, 2018) ^[11]. This reduction in transit time becomes a linchpin in the fight against post-harvest losses, ensuring that a substantial portion of the harvest reaches the market in optimal condition. Beyond the apparent benefit of preserving the physical quality of the produce, this reduction in losses has far-reaching implications (Mane *et al.*, 2022; Bager *et al.*, 2022) ^[8]. It not only safeguards the economic investments of farmers but also contributes significantly to the global imperative of food security by maximizing the utilization of agricultural resources (Pera *et al.*, 2023) ^[45].

5. Access to Credit and Financing

Access to credit and financing emerges as a transformative facet within the context of a transparent and well-organized supply chain in agriculture. The transparency inherent in such supply chains serves as a catalyst in enhancing the creditworthiness of farmers. By providing a clear and verifiable record of transactions, it instills a higher degree of trust and confidence among financial institutions (Khan *et al.*, 2022) ^[29]. Financial institutions, recognizing the reliability and accountability established by transparent supply chains, become more inclined to extend financial support to farmers participating in these organized systems. This newfound access to credit and financing becomes a cornerstone for agricultural development, empowering farmers to make strategic investments in essential resources such as equipment, seeds, and technology (Dujak *et al.*, 2019) ^[17].

6. Empowerment through Information

Empowerment through information takes center stage in the paradigm of transparent supply chains within the agricultural sector. By leveraging block chain technology, these supply chains offer farmers not just transparency but a wealth of real-time information encompassing market demand, pricing dynamics, and evolving consumer preferences (Balaska *et al.*, 2023) ^[9]. This dynamic access to timely and accurate information becomes a potent tool, empowering farmers to elevate their decision-making processes (Yadav *et al.*, 2020) ^[58]. Armed with insights into market trends, pricing fluctuations, and consumer behaviors, farmers can strategically plan their production, optimizing their agricultural practices for maximum efficiency (Peladarinos *et al.*, 2023; Torky *et al.*, 2020; Rehman *et al.*, 2023) ^[44, 55, 47]. This informed decision-making not only enhances the overall productivity of individual farmers but also contributes to the resilience and adaptability of the entire agricultural ecosystem.

7. Quality Improvement and Certification

Quality improvement and certification, fostered by transparent supply chains, constitute a pivotal stride in elevating agricultural products to new standards. The transparency inherent in well-organized supply chains serves as a bedrock for implementing robust quality control measures throughout the agricultural journey (Abiri *et al.*, 2023; Merrell, 2022; Xiong *et al.*, 2020) ^[2, 33, 57]. This meticulous scrutiny allows farmers to adhere to specific standards, not only meeting but exceeding the expectations of discerning consumers. As a consequence, the overall product quality experiences a noteworthy enhancement, ensuring that the produce meets or surpasses industry benchmarks (Rejeb *et al.*, 2020) ^[48].

8. Risk Mitigation

Risk mitigation, facilitated by an organized and transparent supply chain, emerges as a linchpin for farmers navigating the complexities of market fluctuations and uncertainties (FAO, 2021). The systematic nature of these supply chains equips farmers with invaluable tools to identify, assess, and proactively address potential risks (Panwar *et al.*, 2023) ^[42]. By providing a structured framework for information flow, farmers gain access to reliable data, enabling them to make informed decisions in the face of market dynamics (Baz, & Ruel, 2021) ^[19]. This access to timely and accurate information becomes a strategic shield, allowing farmers to anticipate changes in demand, commodity prices, and market trends, thus empowering them to make timely adjustments to their production strategies.

9. Efficient Resource Utilization

Efficient resource utilization, a cornerstone of sustainable agriculture, is markedly enhanced by the integration of block chain technology into transparent and well-organized supply chains. The deep insights provided by understanding market demand and supply chain dynamics empower farmers to make judicious decisions regarding resource allocation (Wang *et al.*, 2019; Duan *et al.*, 2024; Dutta *et al.*, 2020) ^[57, 16, 18]. This strategic understanding allows them to optimize the utilization of vital resources such as water, fertilizers, and other inputs in alignment with actual market needs (Panwar *et al.*, 2023) ^[42]. By aligning resource allocation with real-time demand, farmers not only enhance the overall efficiency of their operations but also contribute significantly to the broader goals of sustainability and cost-effectiveness.

Strategies to enhance the effectiveness of block chain for smallholder farmers

Improving the efficiency of block chain technology for smallholder farmers requires a thoughtful approach that addresses their specific needs and challenges. Here are several strategies to enhance the effectiveness of block chain for smallholder farmers, ultimately contributing to the improvement of their livelihoods:

1. User-Friendly Interfaces

One key strategy is the development of intuitive and user-friendly interfaces, ensuring that applications are designed with accessibility in mind, catering to farmers with limited technical knowledge. By prioritizing simplicity and ease of use, these interfaces become a gateway, empowering smallholder farmers to seamlessly integrate block chain technology into their agricultural practices (Zulkaflī *et al.*, 2017; Lv *et al.*, 2023) ^[60, 32]. Such an approach acknowledges the diverse backgrounds and technological literacy levels prevalent among smallholder farmers, making block chain solutions more inclusive and ensuring that they derive tangible benefits from these innovations (Demestichas *et al.*, 2020) ^[14].

2. Localized Language and Support

Localized Language and Support play a pivotal role in ensuring the widespread adoption of block chain technology among smallholder farmers. By providing comprehensive support and information in local languages, the barriers to understanding and navigating block chain applications are effectively dismantled (Noor, 2022; Pang *et al.*, 2024) ^[37, 41]. This approach not only facilitates a smoother onboarding process for farmers with limited technical literacy but also ensures that they can harness the full potential of block chain solutions tailored to their unique needs and contexts. Empowering smallholder farmers with accessible and localized support goes beyond mere assistance; it becomes a catalyst for their active participation in the digital transformation of agriculture, fostering a sense of inclusivity and ensuring that the benefits of block chain technology are maximized across diverse linguistic and cultural landscapes (Ordonez *et al.*, 2024) ^[38].

3. Mobile Accessibility

Mobile Accessibility stands as a strategic imperative in the integration of block chain technology into agriculture. The overarching strategy involves not just designing but meticulously crafting block chain applications to be inherently mobile-friendly and seamlessly compatible with feature phones. This approach recognizes the ubiquity of mobile devices in rural and remote areas, where feature phones often prevail as the primary mode of communication and information access (Awan *et al.*, 2021) ^[7]. By prioritizing mobile accessibility, block chain developers aim to bridge the digital divide, ensuring that even farmers with basic mobile devices can effortlessly engage with and benefit from block chain applications (Xiong *et al.*, 2020) ^[57]. This strategy not only democratizes access to technological advancements but also empowers a broader spectrum of farmers, irrespective of their access to sophisticated gadgets, to partake in the transformative potential of block chain in agriculture.

4. Training and Capacity Building

Training and Capacity Building form the linchpin of a comprehensive approach aimed at equipping smallholder farmers with the requisite knowledge and skills to harness the benefits of block chain technology. The strategy entails not merely conducting training programs but designing immersive

and tailored initiatives that go beyond mere theoretical knowledge. By actively engaging farmers in hands-on learning experiences, these programs empower them to understand the intricacies of block chain technology and its practical applications in their agricultural pursuits (FAO, 2018). Capacity-building efforts extend beyond a one-time event, fostering an ongoing learning culture that enables farmers to adapt to evolving technologies and glean maximum utility from block chain solutions (Mirabelli & Solina, 2020) ^[35]. Through this multifaceted approach, farmers are not only educated on the transformative potential of block chain but are also nurtured into adept users, capable of integrating this innovative technology seamlessly into their daily farming operations (Srikanth *et al.*, 2022; Pal *et al.*, 2019) ^[53, 40].

5. Incentivize Adoption

Incentivize Adoption by implementing dynamic mechanisms, such as token-based rewards or exclusive discounts, strategically designed to motivate and propel smallholder farmers towards the seamless adoption of block chain solutions (Akella *et al.*, 2022; Chuanheng *et al.*, 2021) ^[4, 13]. This approach goes beyond a mere introduction of incentives; it involves creating a structured system that recognizes and appreciates the farmers' commitment to embracing innovative technologies. By aligning incentives with tangible benefits, such as reduced transaction costs or enhanced market access, this strategy not only stimulates initial adoption but also cultivates a sustained enthusiasm for integrating block chain into their agricultural practices (Esmaeilzadeh, & Mirzaei, 2023) ^[21]. In essence, the incentive framework serves as a compelling catalyst, fostering a sense of shared success and mutual benefit that transcends traditional barriers, making the adoption of block chain solutions a mutually rewarding endeavor for both farmers and the agricultural ecosystem at large.

6. Community Engagement

At the center of advancing blockchain applications in agriculture is the creation of strong partnerships and collaborations. This involves more than simply connecting different stakeholders; it requires building genuine synergy among blockchain developers, experienced agricultural professionals, and community-based local organisations (Kumar *et al.*, 2021) ^[3]. By fostering and maintaining such relationships, it becomes possible to harness the full potential of customised solutions tailored to the complex realities faced by smallholder farmers. The collaborative approach envisaged here is not only about combining technical expertise but also about bringing together diverse viewpoints (Feng *et al.*, 2020; Nazarov *et al.*, 2023) ^[22, 36]. Blockchain specialists offer technological innovation, agricultural experts contribute deep knowledge of farming systems, and local organisations add essential insights into the specific social and cultural contexts of the communities they represent (Xiong *et al.*, 2020; Sendros *et al.*, 2022) ^[57, 50].

7. Tailored Financial Services

In acknowledging the unique financial landscape that smallholder farmers navigate, we are committed to pioneering innovative solutions that go beyond the conventional to address their specific economic challenges. At the heart of this endeavor is the development of cutting-edge, block chain-based financial services meticulously crafted to meet the distinctive needs of smallholder farmers (Mhlanga, 2023) ^[34]. The essence of tailored financial services lies in the profound understanding of the intricate financial ecosystems within which

these farmers operate. Block chain technology, with its inherent transparency, security, and efficiency, becomes a powerful tool in reshaping financial inclusion for this demographic (Astuti & Hidayati, 2023) ^[6]. By leveraging block chain, we aim to create a suite of financial services that not only streamline traditional processes but also introduce novel features that enhance accessibility, reduce transaction costs, and mitigate the risks associated with conventional financial channels (Habib *et al.*, 2022; Kampan *et al.*, 2022) ^[25, 28].

9. Scalability and Cost Efficiency

The block chain solutions, recognizing the imperative for scalability and cost-effectiveness is paramount to ensuring widespread adoption and meaningful impact, particularly in resource-constrained environments. Our commitment is deeply embedded in the strategic design of block chain solutions that not only harness the transformative power of this technology but are also tailored to seamlessly navigate the challenges posed by limitations in resources and infrastructure (Dujak *et al.*, 2019; Bosona & Gebresenbet, 2023) ^[17, 10]. The scalability of our block chain solutions is not merely a technical consideration; it is a strategic imperative that envisions the widespread applicability of these solutions across diverse landscapes, including regions with limited access to technological infrastructure. The goal is to create solutions that can efficiently grow and adapt to the evolving needs of users, without compromising on performance or accessibility (Pera *et al.*, 2023; Singh *et al.*, 2022) ^[45, 52].

10. Conclusion

Block chain technology emerges as a potent catalyst, ushering in a transformative era for farmers and agricultural practices. Its multifaceted impact extends beyond conventional boundaries, offering solutions to longstanding challenges in the sector (Xiong *et al.*, 2020) ^[57]. The transparency and traceability it introduces into the agricultural supply chain empower farmers by ensuring fair compensation and opening new avenues for market access. Through the integration of smart contracts, block chain facilitates seamless and secure financial transactions, empowering smallholder farmers with the tools to navigate economic challenges (Panwar *et al.*, 2023) ^[42]. As we navigate the 21st century, the symbiotic relationship between block chain and agriculture underscores the potential for sustainable development, economic resilience, and equitable opportunities for farmers globally.

It encourages environmentally conscious approaches, aligning farming with broader ecological goals. The decentralized nature of block chain fosters community collaboration, providing farmers with a platform to collectively address challenges and share knowledge (Khan *et al.*, 2022) ^[29]. As we witness this technological revolution, it becomes evident that block chain is not merely a tool but a catalyst shaping the future of agriculture. Its role in elevating farmers' livelihoods reflects a paradigm shift towards a more inclusive, transparent, and sustainable agricultural ecosystem (Alobid *et al.*, 2022) ^[5].

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