Sustainable Agriculture Using Block Chain Technologies and Assistive AI

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Abstract- In contemporary farming, guaranteeing product quality and authenticity is essential for sustaining customer confidence and optimizing value. The combination of block chain and AI promotes sustainable farming by providing transparent data systems and enhancing decision-making, tackling issues like food security, resource waste, climate change, and supply chain transparency. Block chain enhances agriculture with traceable food systems, smart contracts, and carbon credit management. AI aids crop predictions and sustainable methods, while challenges include costs, scalability, and unclear regulations. Affordable and scalable solutions are essential, utilizing standardized data-sharing protocols and clear policies. This review examines technologies for sustainable agriculture, highlighting food safety, carbon credit tracking, climate-smart farming, and supply chain efficiency. It discusses challenges like cost and policy frameworks while proposing future research on system compatibility, real-time analytics, and incentives. Collaboration is essential for agricultural resilience and sustainability.

Keywords: Block chain technology, AI, Green Agriculture, Targeted Farming, Accountability, Automated Contracts, Emission Credit Oversight, Climate-Adaptable Agriculture.

I. INTRODUCTION

In topical ages, agriculture has faced experiments in solving difficult problems related to chain management such as sustainability, traceability and transparency. Smart agriculture employs sensors, drones, AI, and machine learning to enhance crop management, irrigation, and pest control, improving yields and efficiency [5]. Bearable agriculture is the basis for addressing global tests such as food security, irrigation, and climate variation. The growing global population necessitates innovative technologies like block chain and AI to enhance agricultural productivity, minimize environmental impact, and promote social equity. Their integration offers unprecedented opportunities for achieving a sustainable and efficient agricultural ecosystem. The integration of AI and block chain technology words to streamline processes, reduce costs and assurance quality products to clients. Block chain technology is pretty common in many agricultural applications. These applications can meet many needs in the product ecosystem, such as improving food safety, controlling food quality through AI and robotics, personal identification, improving business and alliance.

Block chain technology acts as a reliable, open digital record for the agricultural value chain, promoting confidence among participants. Its uses encompass supply chain clarity, origin validation, and automated contracts, aiding farmers via enhanced traceability, lower expenses, fewer mistakes, and improved access to financial resources. The literature on block chain research in agriculture is categorized into four main areas: traceability, architecture and security, information systems, and other applications. Traceability is paramount for ensuring food safety in supply chains, with block chain emerging as a promising solution. Notable case studies from IBM and Walmart demonstrated significant improvements, such as tracing mangoes from farm to fork in just 2.3 seconds [7]. Provenance and Ever ledger utilized block chain for tracking tuna and wine, respectively. Researchers have also integrated Internet of Things (IoT) devices to enhance traceability in agro-food systems. Additionally, block chain's potential in information systems for improving food supply chain efficiency is noted. Moreover, advancements in security architectures aim to address current block chain risks. Besides traceability, applications encompass food safety, sustainable practices, and supportive frameworks for farmer issues, illustrating the multifaceted impact of block chain in agriculture.

Artificial intelligence enhances block chain by delivering data-driven insights and automating farming processes. Technologies like machine learning and computer vision optimize resource use, forecast crop yields, and identify pests. Precision farming allows real-time monitoring of crops, soil, and weather, promoting efficient input usage. AI improves decision-making with actionable insights from historical and current data. Fasal employs machine learning and affordable sensors for remote monitoring, weather forecasting, and nutrient calculations. Their product, "Farmbot," priced at $4000, facilitates complete farming from planting to weed detection using a physical bot and open-source software.

The mixing of block chain with assist AI creates a powerful synergy that increases individual benefits of farmer. Block chain gives security of agricultural data used by AI models, while AI analysis this data to provide proud analytics and program farming operations. in this combination enable applications such as Weather forecasting, Soil health monitoring system, Analysing crop health, Precision Farming, Identifying Plant Diseases, Detecting pest infestations, Agricultural Product Grading, Alerts on Crop Infestation, Detecting weeds, Irrigation, Warehousing that combine block chain-verified environmental data with AI-driven recommendations. Despite their probable, the agreement of these technologies faces significant challenges, including high implementation costs, scalability issues, and fragmented data ecosystems. Collaboration needed among governments, researchers, private sector. Block chain and AI can transform agriculture sustainably, equitably, and productively, aligning with global Sustainable Development Goals.

II. BLOCK CHAIN TECHNOLOGY IN AGRICULTURE

Block chain technology in agriculture distributes control among network members, enhancing security while minimizing corruption risks. It significantly improves traceability, food safety, and sustainable practices. However, challenges remain, notably potential misuse and the difficulties small-scale farmers face in adopting this technology. Key areas needing attention include decentralization, digital literacy, transparency, and ethical practices to empower farmers. Proper data formatting enhances compliance, aiding informed decisions that can improve small-scale farmers' livelihoods.

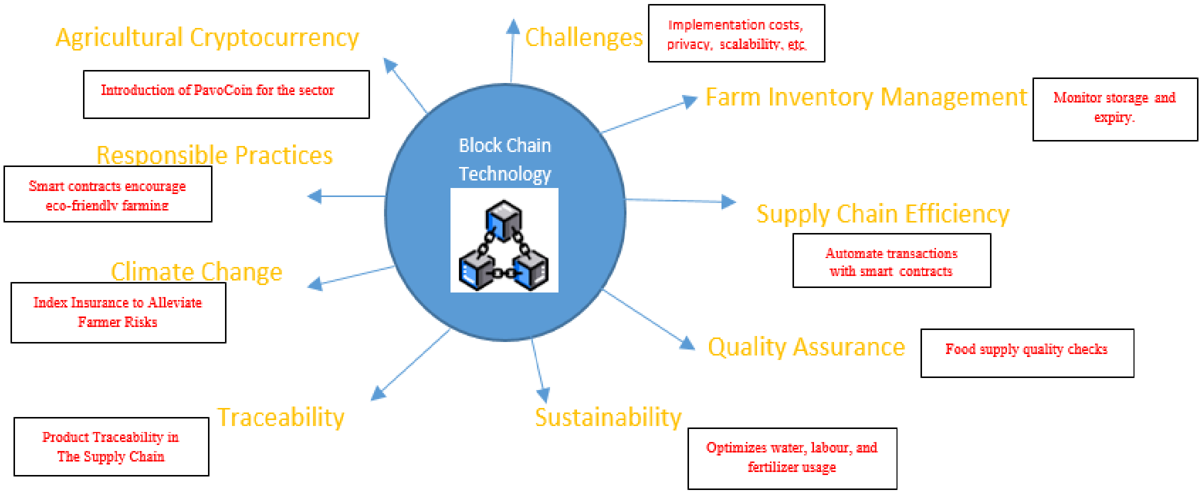

Fig 1: Applications in Blockchain Technology

In agricultural insurance, block chain facilitates index-based systems, offering automated payouts based on objective indices, thus reducing challenges like information asymmetry and basis risk. Prototypes for decentralized crop insurance are being developed by companies like Etherisc and World Cover. Block chain also enhances e-commerce in agriculture, tackling issues such as consumer trust and logistics while improving market access for small farmers through enhanced security and reduced costs. Nonetheless, challenges regarding data authenticity and access to cryptocurrency for developing region farmers remain.

2.1 Traceability and Food Safety

Traceability, defined as "one step back one step forward", allows recall of a food product's origin, per ISO 22005:2007. The EU General Food Law EC 178/2002 elaborates on tracing food through all production stages. A comprehensive traceability system should include detailed information about each ingredient and its journey [15]. Key questions focus on essential data, ownership, data collection tools, and data management. Traceability is categorized as intra-company and external levels, with mandatory and voluntary distinctions influencing its effectiveness and complexity.

Agriculture traceability requires extensive data collection throughout the supply chain. Early manual recording caused inaccuracies; recent automation and IoT advancements improved data collection using barcodes, QR codes, RFID, and WSNs. RFID ensures secure data management from farm to fork, while WSNs monitor agricultural conditions with various sensors [16,17]. Traceability improves consumer safety by facilitating quicker recalls, ensuring transparency and reliability within the complex food supply chain.

Block chain enhances traceability and transparency in agriculture, building trust and food safety. It allows consumers to verify food origins, reducing fraud and contamination risks. IBM Food Trust exemplifies this efficiency. This section outlines key elements of block chain governance: Access control specifies user roles and permissions; data management includes protocols for data handling; quality assurance verifies grain standards; security details protective measures; and dispute resolution defines processes for resolving conflicts[18]. Legal compliance ensures adherence to regulations and involves regular reviews.Our analysis classified 25 use cases through cross-mapping thematic areas with attributes. Preliminary findings emphasize blockchain transparency across various stages, urging a careful examination of technology limitations that may hinder adoption and scalability in agri-food supply chains [19].

Blockchain Feature	Role in Traceability	Real-World Example	Impact
Decentralized Ledger	Tracks every transaction across all network nodes	IBM Food Trust enables transparent tracking of food from farms to consumers, reducing fraud and contamination risks[9][8].	Ensures secure, auditable records while fostering trust and accountability among stakeholders.
Immutability	Prevents tampering by making recorded data permanent	AWS IoT-enabled blockchain tracks perishable goods, ensuring tamper-proof temperature records during transit[10].	Builds trust with consumers and regulators by guaranteeing data integrity and reducing fraud risks.
Real-Time Updates	Provides live product tracking	Maersk's TradeLens platform tracks shipping containers in real-time, improving logistics efficiency[8].	Enhances supply chain visibility, enabling faster issue resolution and better operational decision-making.

Table 1: Block chain Features Enhancing Traceability

Table 1 outlines how block chain features—Decentralized Ledger, Immutability, Real-Time Updates—enhance traceability in various applications. By presenting examples like IBM Food Trust and Trade Lens, it illustrates the impact on trust, data integrity, and operational efficiency across industries. Only 12 studies apply big data analytics in blockchain-based food traceability. Combining these technologies improves monitoring, reduces waste, enhances safety, and aids herd management, with practical applications observed in China's agri-food sector.

2.2 Smart Contracts for Farmers

The impact of smart contracts in agriculture and food sectors through an analysis of over 130 articles from 2010 to 2023, highlighting methodologies, applications, real-world implementations, and inherent challenges. It emphasizes their benefits, such as transparency, efficiency, and peer-to-peer transactions. Proposed by Nick Szabo in 1994, smart contracts automate agreements on block chains, minimizing fraud and transaction costs. Ethereum led their adoption, and their lifecycle includes negotiation and deployment phases. A cryptocurrency functions as a digital asset secured by cryptography, while smart contracts operate within a virtual environment for transaction processing [20].

The evaluation criteria for agrobiodiversity contracts includes performance standards, participation, and compliance. Strengths include the incorporation of relevant standards and contract freedom, fostering biodiversity. However, some biodiversity aspects, like non-industrial cultivars, may be overlooked. The separation of powers can enhance sustainability by reducing dependence on a single company, but it can also concentrate power leading to sustainability violations. Transparency can facilitate learning among growers, yet limited visibility can breed suspicion. Compliance varies, with spontaneous compliance driven by contract freedom, while control can create conflicts of interest [21]. Monitoring reinforces compliance but incurs costs, and feedback mechanisms require proactive engagement from parties for sustainable practices. Smart contracts automate agreements between farmers and buyers, ensuring fairness and reducing transaction delays.

Category	Description	Impact	Example/Application
Block chain Adoption in Agribusiness	Blockchain is standardizing payment transactions and creating equitable opportunities for farmers and harvesters.	Facilitates financial inclusion, especially in impoverished regions, by ensuring fair and secure payments.	Global initiatives in trade finance to improve trust and security in international agricultural transactions.
Market Growth	Blockchain in agriculture projected to grow from $41.2M (2017) to $430M (2023) at a 47.8% CAGR.	Highlights the rapid adoption and potential economic transformation of the agriculture sector.	Agritech startup's and platforms scaling blockchain solutions in rural farming communities.
Smart Contracts	Automates transaction execution based on predefined criteria, reducing ambiguity and fostering trust.	Eliminates intermediaries, enhances transparency, and simplifies financial processes.	Smallholders using smart contracts for installment payments of equipment or materials.
Transparency in Crop Pricing	Blockchain enables streamlined crop price tracking and fair transaction processing.	Reduces discrepancies, mitigates fraud, and builds a more transparent supply chain.	Platforms providing shared access to price data for all stakeholders, ensuring fair market pricing.
Challenges in Implementation	Issues like sluggish banking transactions and counterfeiting in supply chains hinder efficiency.	Risks include financial losses and delays, particularly for small-scale farmers.	Blockchain tackling counterfeit fertilizers worth €1.3B in losses as reported in African agriculture.
Auditing & Accountability	Smart contracts provide an indefinite and secure record of transactions for auditing.	Reduces audit costs and enables continuous, transparent audits instead of periodic evaluations.	Auditors leveraging blockchain to verify real-time payment and transaction data directly.
International Trade Security	Digitizes real-time billing and payment for cross-border transactions, improving efficiency.	Reduces costs, minimizes risks, enhances cash flow.	streamlining trade finance processes for SMEs in agriculture.
Future Opportunities	Agriculture lags in adopting blockchain but has immense potential for transformation via automation.	Boosts innovation in aggrotech, enhances trust among stakeholders, and streamlines pre- and post-harvest operations.	Smart contracts enabling autonomous operations in agribusiness while promoting equity and efficiency.

Table 2: Benefits of Smart Contracts in Agriculture

The table organizes block chain technologies and challenges, emphasizing impact on trust, efficiency, transparency, and financial inclusion in agriculture.

2.3 Carbon Credit Management

Block chain technology can transform the carbon credit system by enhancing trust and transparency. With issues like fraud and double-counting eroding confidence, block chain's immutability ensures valid transactions. This technology fosters corporate environmental responsibility, motivating companies to embrace carbon credits. Additionally, it addresses standardization and verification challenges, akin to IBM Food Trust's impact on food supply chain transparency and efficiency.

Block chain records carbon sequestration accurately, allowing farmers to earn and trade carbon credits. Real-time data access is crucial in the carbon credit market, with block chain enabling informed decisions and project tracking. Its transparent transaction record promotes quick issue resolution. Moreover, decentralized block chain governance mitigates regional regulatory disparities, ensuring consistent oversight and operation free from biases in the carbon credit process. The distribution of carbon credits earned through activities like cover cropping, reforestation, and reduced emissions farming.

Blockchain Capability	Function	Outcome
Transparent Ledger	Verifies carbon storage data	Enables reliable credit trading
Immutable Records	Protects against fraud	Increases market credibility
Tokenization	Issues tradeable credits	Simplifies carbon market participation

Table 3: Block chain's Role in Carbon Credit Management

2.4 Supply Chain Optimization

Block chain enhances supply chain efficiency through real-time tracking, reducing spoilage, optimizing logistics, and refining storage management via features like data sharing, tamper-proof records, and smart contracts. Supply Chain Management (SCM) is critical in connecting producers to consumers. Issues in agricultural supply chains include corruption among intermediaries, lack of transparency, and accountability. To address these challenges, a block chain-enabled system is proposed to enhance security and transparency. Blockchain, as decentralized Distributed Ledger Technology (DLT), provides tamper-proof data storage with cryptographic security. It also facilitates tracking food product origins and integrates IoT devices for real-time quality updates, such as soil quality and temperature. The FARMAR project aims to create a reliable web application for sustainable supply chains, utilizing various technologies like Big chain DB and Smart Contracts.

III. ASSISTIVE AI IN AGRICULTURE

AI technologies enhance efficiency across industries, notably in agriculture, addressing challenges like crop yield and irrigation. Agricultural robots and UAVs optimize production, enabling farmers to increase output with reduced input. By 2050, AI will automate processes, helping farmers meet the demands of a growing urban population. variety selection and seed quality dictate maximum plant performance [6]. Emerging technologies enhance crop selection and hybrid seeds, adapting to environmental factors to reduce disease risk. Additionally, AI-powered chatbots assist farmers with personalized support, advice, and recommendations, addressing their queries effectively. Applications include precision agriculture with data collection via sensors and drones, AI for pest management, yield forecasting through machine learning, and autonomous systems for planting and harvesting tasks.

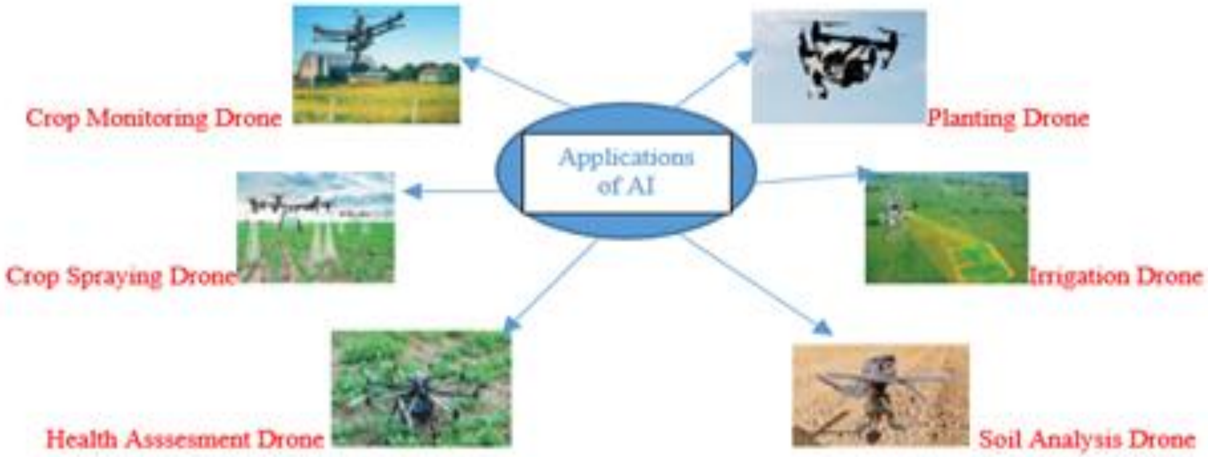

Figure 2: Overview of AI Applications in Agriculture

3.1 Precision Agriculture

Precision agriculture improves crop management by utilizing data from various sources at local scales (< 5 m). Despite its significance, remote sensing adoption has been slow. However, advancements in high-resolution satellite imagery and low-cost UAV technology are driving progress. Integrating multiple data sources, including CubeSat's for efficiency, is crucial. Recent innovations in UAVs, like multirotor and fixed wings, along with diverse sensors ranging from basic cameras to advanced hyperspectral systems, are enhancing remote sensing capabilities in agriculture. AI tools analyze sensor, drone, and satellite data to optimize resources and enhance crop yields.

3.2 Pest and Disease Management

AI-based model for predicting crop diseases and pest outbreaks, utilizing satellite imagery, meteorological data, historical records, and IoT sensor data. It includes recurrent neural networks (RNNs) for time-series analysis and convolutional neural networks (CNNs) for satellite imagery. The model has demonstrated superior accuracy in predicting epidemics compared to traditional methods, providing farmers with early warnings to mitigate biotic threats. This predictive capability aids agronomists and policymakers in enhancing pest control, fostering sustainable agriculture and food security. AI models forecast pests, plant diseases, ensuring timely interventions. [22].

3.3 Predictive Analytics for Yield Optimization

Precision agriculture leverages technology to boost crop yields, minimize waste, and enhance resource efficiency. Utilizing analytics, remote sensing, and IoT data, farmers can proactively address issues like diseases and deficiencies. Deep learning models are effective in detecting crop health problems and forecasting yields by analyzing historical data. Meanwhile, traditional farming faces challenges from resource scarcity and climate change. Research shows various deep learning models, especially 2D and 3D CNNs, achieving impressive accuracies of 90% to 97% in crop monitoring and disease classification [23].

3.4 Autonomous Systems

Autonomous farming technologies are transforming agriculture, enhancing efficiency and productivity in operations.AI powers autonomous machinery like drones and robots for planting, weeding, irrigation, and harvesting, reducing labour dependency.

IV. INTEGRATING BLOCK CHAIN AND AI FOR SUSTAINABLE AGRICULTURE

The integration of block chain and AI creates a smart agriculture can enhance productivity and sustainability in farming, prompting future research on developing a more secure and eco-friendly food system.

Fig 3: Image of A Digital Farm Utilizing AI and Block Chain[26].

4.1 Data Integrity for AI Models

Blockchain ensures that data used by AI models is secure, traceable, and tamper-proof, improving decision-making accuracy. Data drives modern agriculture, enabling insights on farming processes, market trends, and optimizing yields through AI-powered analytics and management software.

4.2 Decentralized AI Training

Decentralized AI combines Artificial Intelligence with block chain, enabling machines to replicate human-like decision-making while securely storing data across a network. Miners can contribute computing power for collaborative AI model training, enhancing transparency and governance. This decentralized model promotes diverse developer input, yielding a robust and inclusive system. It leverages token-based rewards, ensuring efficient AI access. Additionally, it enhances performance, reduces bias, and strengthens security through local processing and block chain's immutable features. Farmers can share agricultural data securely using blockchain, enabling decentralized AI model training while protecting data privacy.

4.3 Smart Farming Systems

Emerging innovations in agriculture include AI-powered precision agriculture for optimized planting and irrigation, AI-driven genetic crop improvement for resilient varieties, smart irrigation systems for efficient water use, autonomous machinery for operational tasks, block chain-enabled supply chain transparency, predictive maintenance for equipment, and AI-enhanced climate adaptation strategies for informed decision-making.AI-powered IoT devices collect real-time data from fields, while blockchain stores and authenticates this data for enhanced farm management.

4.4 Incentivizing Sustainable Practices

Market-based strategies can improve space debris risk reduction by introducing economic incentives such as taxes or subsidies, while addressing current governance challenges. Mechanisms like marketable permits and regulatory fees can internalize debris generation costs, promoting compliance. Multilateral efforts are crucial for effective governance and equitable responsibility distribution. Blockchain-based reward systems can issue tokens or credits for adopting sustainable farming methods, tracked and verified by AI analytics.

V. APPLICATIONS OF BLOCKCHAIN AND AI IN SUSTAINABLE AGRICULTURE

The future of Indian farming lies in smart farming, utilizing AI, IoT, and blockchain for efficient management [24]. Key strategies include precise pesticide application, soil moisture monitoring, and integrating technology for better productivity, transparency, and collaboration. These innovations improve agricultural efficiency and sustainability.

Application	Technology	Real-Time Example	Adoption Ratio/Percentage
Supply Chain Transparency	Block chain	IBM Food Trust: Used by Walmart and Nestlé to track the origin and journey of agricultural products.	~25–30% of large-scale supply chains in developed markets.
Crop Monitoring & Yield Prediction	AI	John Deere's AI-driven precision agriculture tools for crop health monitoring and yield optimization.	~40% of advanced farming operations globally.
Smart Contracts for Farmer Payments	Block chain	AgriDigital: Enables instant payments to farmers once produce is delivered and verified.	~15–20% adoption among smallholder and contract farming.
Pest and Disease Detection	AI	PEAT's Plantix App: Uses AI to identify crop diseases via images uploaded by farmers.	~35% adoption in regions like Asia and Africa.
Traceability and Certification	Block chain	Provenance: Tracks the journey of organic produce from farms to consumers to ensure authenticity.	~20–25% adoption in organic and specialty farming.
Weather Prediction and Disaster Response	AI	IBM Watson Decision Platform: Provides hyper-local weather forecasts to farmers.	~50% usage in weather-dependent farming regions.
Sustainable Water Management	AI + Block chain	Riddle&Code: Blockchain-backed IoT sensors track water usage, paired with AI to optimize irrigation.	~10–15% in water-scarce agricultural regions.
Market Access for Farmers	Block chain	BanQu: Connects small farmers to global markets via blockchain-based identity and supply chain solutions.	~5–10% adoption in developing economies.

Robotics and Automation	AI	Blue River Technology: AI-powered precision sprayers reduce chemical use in farming.	~30% adoption in industrialized farming.

Table 4: Key Applications of Blockchain and AI in Agriculture

This table reviews some Adoption ratios in agriculture vary by region and farm size, with block chain and AI growth potential increasing due to better connectivity and lower costs.Block chain ensures secure tracking and verification in food traceability, carbon credits, and decentralized marketplaces, while AI enhances efficiency in precision agriculture, smart irrigation, and contamination detection.

VI. CHALLENGES AND LIMITATIONS

Blockchain and AI in agriculture encounter significant challenges. Regulations vary globally, complicating adoption. Developing nations face digital gaps, lacking resources and expertise. Privacy issues stem from access key loss, while transaction delays impede financial operations. Rising storage demands and energy costs hinder accessibility for small and medium enterprises, limiting their potential usage.

6.1 High Costs and Complexity

Implementing blockchain and AI systems demands significant financial and technical resources, posing challenges for small-scale farmers with limited budgets and expertise. Infrastructure costs include investments in internet connectivity, IoT devices, and secure servers, while AI requires advanced computing systems. Additionally, farmers often lack access to necessary training. For instance, AgriDigital, a blockchain platform in Australia, faced difficulties in reaching smaller farming communities due to high onboarding costs and required technical skills. Similarly, AI-driven crop monitoring in India struggles in rural areas where farmers cannot afford essential technology and services.

6.2 Scalability Issues

Blockchain networks, particularly public ones, struggle with scalability due to the massive data generated in agriculture. Farms equipped with IoT sensors produce terabytes of data daily, causing transaction processing delays and storage issues. The decentralized structure of blockchain also contributes to latency problems, leading to slower transaction speeds in resource-limited environments. A case in point is IBM Food Trust, which encountered scaling difficulties while managing real-time data during peak harvests. Additionally, users of Ethereum-based solutions face high transaction fees and delays amidst network congestion, hindering efficient adoption.

6.3 Data Integration

Agriculture suffers from fragmented and unstandardized data sourced from drones, satellites, and IoT devices, complicating AI model training and blockchain use. Data silos arise as farms utilize varied systems for monitoring, demanding extensive integration efforts. The absence of global standards for agricultural data formats further impedes interoperability. A case in point is John Deere, where AI precision tools struggled with inconsistent data formats from third-party sources, delaying insights. In Ethiopia's coffee farming, blockchain projects encountered inefficiencies due to manual, error-prone data entry.

6.4 Policy and Regulation

Governments globally lack defined legal frameworks governing blockchain and AI in agriculture, leading to uncertainty in data ownership, privacy, liability, and compliance. Farmers are concerned about data ownership and legal ambiguities, which deter investment in these technologies; for instance, liability in AI errors is debated. In the EU, clear data protection rules exist (GDPR), yet no specific policies address blockchain and AI in agriculture, hindering traceability projects. In Kenya, blockchain smart contracts for payments encounter legal challenges due to unrecognized enforceability.

Summary of Challenges

Challenges in agriculture include high costs and complexity, limiting smallholder farmers' adoption. Potential solutions involve subsidies, government funding, and farmer cooperatives. Scalability issues arise from limited blockchain transaction speeds, which can be addressed by Layer-2 solutions or private blockchain networks. Fragmented data hampers AI training, necessitating global agricultural data standards. Lastly, unclear policies create legal uncertainties, suggesting the need for sector-specific regulations on data ownership and smart contracts. Collaboration is essential for effective solutions.

VII. FUTURE RESEARCH DIRECTIONS

Future research on blockchain and AI in sustainable agriculture should emphasize interoperability standards for data exchange, cost-effective solutions for smallholder farmers, edge computing for real-time insights, and supportive policies from governments to foster adoption while safeguarding farmers' data rights.

VIII.CONCLUSION

Blockchain technology can enhance agriculture's efficiency, transparency, and sustainability by decentralizing control, reducing corruption, and improving traceability. When paired with AI applications like precision agriculture, they boost productivity but face challenges for small-scale farmers, including high costs and digital literacy gaps. Collaborative efforts in education and access are needed. Addressing cost, scalability, and regulatory issues is essential for broad acceptance and realizing sustainable agriculture benefits for all.

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