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RESEARCH ARTICLE

Exploring the Blockchain's Green Revolution in Medicinal Plant Supply Chains (Blossoming Trust) – A Review

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ABSTRACT

The integration of blockchain technology in the cultivation, farming, conservation, and propagation of medicinal plants and organic farming offers a transformative solution to address key challenges in these industries. This study examines blockchain's potential to revolutionize these practices by enhancing supply chain traceability, provenance verification, and fair-trade promotion through smart contracts. Utilizing a systematic approach in descriptive analysis, the review investigates blockchain's role in fostering collaboration, transparency, and innovation, contributing to sustainable and ethical sourcing in medicinal plant supply chains. The methodology relies on secondary data, guided by specific research questions targeting blockchain's ability to address challenges in traceability, fraud prevention, and environmental sustainability in the medicinal plant sector. These questions align with the study's objectives, enabling an organized examination of blockchain's applications and benefits. Data collection involves sourcing from peer-reviewed journals, industry reports, and case studies from databases such as PubMed, IEEE Xplore, and ScienceDirect, focusing on studies published from 2013 to 2023. Inclusion criteria are based on relevance to themes like fraud prevention, transparency, and ecological impact in medicinal plant supply chains, alongside blockchain's broader implications. Data extraction and analysis identify key themes, including blockchain's applications, benefits, and barriers to adoption, highlighting its potential to improve traceability, authentication, and eco-friendly practices within medicinal plant transactions. The methodology includes diagrammatic representations illustrating blockchain's role across each supply chain phase, from sourcing and certification to end-user delivery, to clarify transaction flows and underscore blockchain's transformative impact. Despite implementation challenges, this study argues that blockchain offers considerable potential for sustainable medicinal plant resource management. By addressing literature gaps regarding blockchain's impact on biodiversity and ethical sourcing, the review raises awareness and advocates for the technology's adoption. With innovation and collaboration, stakeholders can unlock blockchain's full potential, promoting a resilient, ecologically conscious future for global herbal medicine production. In conclusion, blockchain is highlighted as a powerful tool for enhancing transparency, accountability, and regulatory compliance in the medicinal plant industry, fostering responsible resource management and sustainable practices.

Keywords*: *Blockchain, Medicinal Plants, Supply Chain Management, Sustainability, Innovation

INTRODUCTION

At the heart of nature's pharmacy lies a treasure trove of medicinal plants, each capable of healing, calming, and revitalizing animals and nature. However, as our world evolves, so do the challenges facing these botanical wonders. The delicate balance between human health and environmental conservation necessitates a paradigm shift in how we approach the cultivation, farming, conservation, and propagation of these precious resources (Martin *et al.*, 2016). Similarly, innovation meets tradition in sustainable agriculture, organic farming, conservation, and medicinal plant propagation, where the future of healthcare directly intersects with biodiversity conservation. On the other hand, in this advancing age of environmental consciousness and scientific enlightenment, the quest for sustainable solutions has never been more urgent or promising (Ehrlich, 2002).

Sustainable farming embodies a holistic ethos, weaving together the threads of environmental stewardship, agricultural innovation, and community resilience. It is a testament to our commitment to nurturing the land, replenishing its bounty, and protecting the complex web of life that sustains us all. From regenerative farming practices that bring life back to depleted soils to agroforestry systems that integrate diverse ecosystems, sustainable agriculture is a beacon of hope in an era of environmental uncertainty (Dessart *et al.*, 2019). Organic farming, with its unwavering commitment to purity and integrity, stands as a beacon of light in a sea of chemical-laden agribusiness. It demonstrates our respect for the wisdom of nature, the sacredness of the soil, and a commitment to producing food and medicine in harmony with the earth (Frey, 2011). Through practices like composting, cover cropping, and biological pest management, organic farmers nurture not only the health of the land but also those who share in its bounty.

Correspondingly, forest conservation the silent guardian of biodiversity remains a bulwark against the tide of extinction, protecting species both large and small. In a world teetering on the brink of ecological collapse, conservation is not merely an option but a necessity and a moral responsibility to protect our planet's irreplaceable wealth for future generations (Carlisle, 2022). Through protected areas, habitat restoration, and sustainable harvesting methods, conservationists work tirelessly to ensure that biodiversity remains intact, vibrant, and resilient.

The art of propagation, renewal, and regeneration holds the key to unlocking the limitless potential of medicinal plants for generations to come. It is a journey of discovery, innovation, and collaboration, highlighting people's respect for individual ingenuity, adaptability, and the healing power of nature. From seed saving to tissue culture and from traditional knowledge to cutting-edge biotechnology, these practices chart a course toward a future where every seed is a promise, every plant is a legacy, and every harvest is a celebration of life. Thus, in the sustainable cultivation, organic farming, conservation, and propagation of medicinal plants, we find ourselves at the crossroads of tradition and innovation, stewardship and discovery, conservation and progress (Ndawonde, 2015). It is in this sacred space between the past and future that we must summon the courage, vision, and determination to forge a new path that honors the wisdom of our ancestors while embracing the challenges of our time. Human and planetary health indicate a future that is not merely compatible but inseparably linked.

The objective of this review article is therefore to explore the potential of blockchain technology to revolutionize medicinal plant cultivation, farming, conservation, propagation, and supply chain management. By achieving these goals, it seeks to improve understanding and awareness of blockchain's role in promoting sustainable management practices in medicinal plant industries and, ultimately, to contribute to biodiversity conservation and the availability of natural remedies for future generations.

Additionally, this review comprehensively analyzes and interprets findings from the existing literature on blockchain's role in medicinal plant supply chains. By examining trends, common practices, and challenges, it highlights current knowledge gaps and inconsistencies in the research landscape. The discussion also interprets these findings, addressing blockchain's specific contributions to transparency, fraud prevention, and sustainable harvesting practices. Additionally, it considers the implications of blockchain adoption for industry stakeholders, such as farmers, suppliers, and consumers, emphasizing its potential to enhance trust, traceability, and ecological preservation.

MATERIALS AND METHODS

This study is designed to follow a systematic approach to descriptive analysis, focusing on secondary data to assess the role of blockchain technology in enhancing sustainability and transparency within medicinal plant supply chains. The review begins by formulating specific research questions that target blockchain’s potential to address common supply chain challenges. These questions explore how blockchain can improve traceability, prevent fraud, and support environmentally sustainable practices within the medicinal plant industry. The formulation of these questions is guided by the primary objectives of the study and ensures a clear alignment between the research goals and the analysis process.

Data collection focuses on gathering secondary sources from peer-reviewed journals, industry reports, and relevant case studies. The search is conducted across databases such as PubMed, IEEE Xplore, and ScienceDirect to capture studies from 2013 to 2023 that discuss blockchain applications in supply chains, green technology solutions, and medicinal plant trade. Inclusion criteria are established to maintain relevance and include publications that address challenges like fraud, transparency, and environmental impact in medicinal plant supply chains, as well as the broader implications of blockchain technology on these challenges. Data extraction and analysis are conducted by identifying and categorizing key themes, such as blockchain’s applications, benefits, barriers, and potential to enhance sustainability. These themes are structured to emphasize findings on traceability, authentication, and eco-friendliness within blockchain-supported medicinal plant transactions, providing an organized view of blockchain's impact on medicinal plant supply chains.

To enhance clarity and understanding, the methodology is supported with diagrammatic representations illustrating blockchain's role across each phase of the supply chain, from sourcing and certification to transportation and end-user delivery. These diagrams aim to simplify complex transaction flows and emphasize blockchain's transformative potential for transparency and trust in the medicinal plant supply chain.

This systematic approach, structured analysis, and inclusion of diagrammatic representations will deepen readers' understanding of blockchain's role in fostering trust, transparency, and sustainability in medicinal plant supply chains.

RESULTS AND DISCUSSION

Understanding the importance of traceability and transparency in medicinal plant industries

The medicinal plant industry faces significant challenges related to traceability and transparency, stemming from issues such as derivation, mislabeling and unsustainable sourcing practices. Traceability ensures that the journey from medicinal plant cultivation to consumption can be accurately documented, enabling stakeholders to verify authenticity, quality and ethical sourcing practices. Transparency, on the other hand, fosters trust and accountability by providing stakeholders, including consumers, access to detailed information about medicinal plant production, processing and distribution (Wognum *et al.*, 2011; Vian and Kohler, 2016).

But many medicinal plants are at risk due to overharvesting, habitat destruction and climate change. Traceability and transparency initiatives should help monitor the sourcing of these plants, ensure sustainable practices are adopted to conserve biodiversity and support local communities that depend on these resources (Beck-O'Brien and Bringezu, 2021; Salmi *et al.*, 2023). Also, traceability allows for better quality control throughout the supply chain. By tracking the origin of medicinal plants from cultivation to processing and distribution, companies are able to identify potential contaminants, contaminants or other quality issues, ensuring the safety and efficacy of the final products (Tripathy *et al.*, 2015; Nafiu *et al.*, 2017). Transparency in the medicinal plant industry is essential to ensure ethical sourcing practices. This includes fair trade, respect for indigenous knowledge and intellectual property rights, as well as fair benefit sharing with local communities involved in plant cultivation and harvesting (Sanghera *et al.*, 2015; Liu *et al.*, 2023). Similarly, many countries have regulations and standards that govern the trade in medicinal plants and herbal products. Traceability systems help companies comply with these regulations by providing documentation and evidence of legal and sustainable sourcing practices (Nikolakis *et al.*, 2018; Hastig and Sodhi, 2020). Increasingly, consumers are demanding transparency and accountability from companies regarding the products they purchase, including herbs and herbal supplements. By implementing traceability measures and providing transparent information about sourcing and production practices, companies can build trust with consumers and enhance brand reputation (Brown, 2017; Obahiagbon and Ogwu, 2023).

On the other hand, advances in technology such as blockchain, RFID (radio-frequency identification) and DNA barcoding are being used to improve traceability in the medicinal plant industry. These technologies enable real-time tracking of products throughout the supply chain, reducing the risk of fraud and ensuring authenticity (Galvez *et al.*, 2018; Mehannaoui *et al.*, 2023). Also, collaboration between industry stakeholders including growers, suppliers, manufacturers, regulators and non-governmental organizations (NGOs) is essential to establish effective traceability and transparency initiatives. Collective efforts can lead to the development of industry standards, best practices, and certification schemes (Gardner *et al.*, 2019; Gurzawska, 2020). In further consideration, continuous research and innovation is needed to further improve the discovery methods and technologies in the medicinal plant industry. This includes developing new analytical techniques for plant verification as well as integrating digital platforms for data sharing and supply chain management (Bargshady *et al.*, 2016; Tian, 2017).

Overview of blockchain technology and its applications in agriculture

Currently, blockchain technology holds great potential for transforming various sectors including agriculture, and decentralized and distributed ledger technology through blockchain records transactions across multiple computers in a tamper-proof and transparent manner. Further, each block of this chain creates a secure and immutable record of the previous block's cryptographic hash, along with the transaction data. That's why in agriculture, blockchain can improve traceability, transparency and efficiency across the supply chain by securely recording transactions, verifying authenticity and facilitating real-time data exchange between stakeholders (Sunny *et al.*, 2020). By leveraging smart contracts and cryptographic techniques, blockchain enables trustless interactions while mitigating the risks associated with fraud, forgery, and data manipulation. On the other hand, blockchain technology has gained significant attention across various industries, including agriculture and supply chains (Rejeb *et al.*, 2019). Because of the ability to improve transparency, traceability and efficiency. The main features of blockchain technology (Lin *et al.*, 2020) can be identified by Figure 1 below.

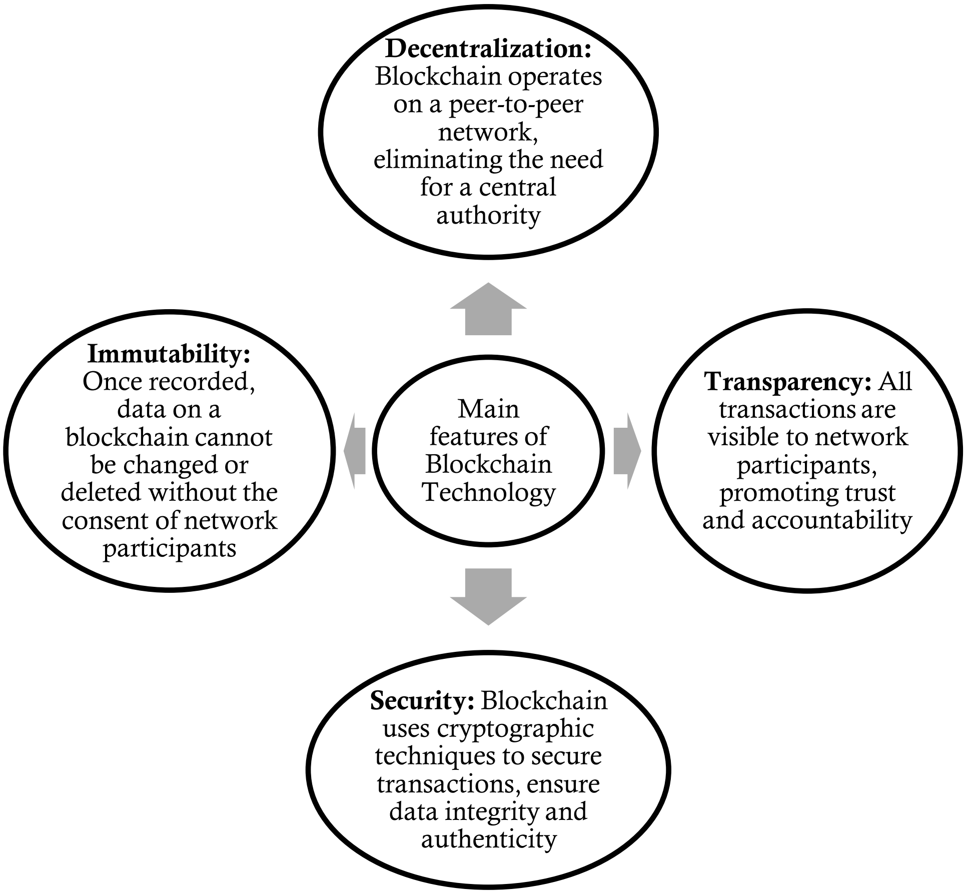

Figure 1: Main features of Blockchain

Blockchain applications in agriculture

Supply chain traceability: Blockchain can provide end-to-end traceability of the agricultural supply chain by recording every stage of production, processing and distribution. Ensures transparency and authenticity, allowing consumers to verify the origin and quality of agricultural products. For example, companies like IBM Food Trust and Walmart are using blockchain for traceability of food products, to respond quickly to food safety issues and reduce food fraud (Ge *et al.*, 2017).

Provenance verification: Blockchain enables farmers to prove the authenticity and quality of their produce by recording relevant information such as planting, harvesting and processing methods to the blockchain. This helps build customer confidence and access premium markets that value provenance (Torky and Hassanein, 2020).

Smart contracts: Smart contracts are self-executing agreements written directly into code with the terms of the agreement. In agriculture, smart contracts can automate various processes such as payment settlements, insurance claims and tax agreements. For example, farmers can enter into smart contracts with buyers or insurers, triggering automatic payments upon meeting predefined conditions such as delivery or crop harvest (Salah *et al.*, 2019).

Asset tokenization: Blockchain facilitates tokenization of agricultural assets such as land, machinery and crops. By representing these assets as digital tokens on a blockchain, ownership can be easily transferred, fragmented and traded, unlocking liquidity and investment opportunities for small-scale farmers (Kiruba *et al.*, 2021).

Data management: Agricultural blockchain platforms can securely manage and share data related to crop yields, weather conditions, soil quality and market prices. Farmers can use this data to make informed decisions based on their production history, optimize resource allocation and access financial services such as credit and insurance (Lin *et al.*, 2020; Yang *et al.*, 2021).

Blockchain solutions for sustainable cultivation practices

It has been recognized that Blockchain solutions can promote sustainable farming practices by enabling farmers to transparently record and monitor their agricultural activities, inputs and results. By immutably documenting factors such as crop rotation, organic inputs and water use, blockchain improves accountability and compliance with sustainability standards. In addition, blockchain-based supply chain platforms can facilitate direct relationships between farmers and consumers, encourage fair trade and environmentally friendly practices, and maintain sustainability throughout the supply chain (Iqbal and Butt, 2020). The latest developments related to blockchain applications in sustainable farming practices can be identified (Figure 2) as follows (Demestichas *et al.*, 2020; Lin *et al.*, 2020; Torky and Hassanein, 2020).

Traceability and Transparency: Blockchain technology enables the recording of every transaction or activity in the agricultural supply chain in an immutable and transparent manner. This helps in tracing the origin of products, ensuring authenticity and maintaining quality standards.

Smart Contracts for Fair Trade: Smart contracts on blockchain platforms can facilitate fair trade practices by automatically executing contracts when predefined conditions are met. This ensures that farmers receive fair compensation for their produce and promotes ethical sourcing practices.

Collaborative Platforms: Blockchain-based collaborative platforms connect farmers, suppliers, distributors and consumers in a transparent ecosystem. These platforms facilitate knowledge sharing, resource pooling and collaborative decision-making to promote sustainable cultivation practices across the agricultural value chain.

Supply chain optimization: Blockchain increases supply chain efficiency by providing real-time visibility into the movement of agricultural products from farm to table. This minimizes delays and waste in the supply chain while reducing the risk of fraud, theft and counterfeit products.

Certification and Compliance: Blockchain can streamline the certification process for sustainable farming practices by securely storing certification and compliance documents in a decentralized ledger. This increases confidence among consumers and facilitates access to premium markets for sustainably produced goods.

Data management and analytics: Blockchain solutions combined with data analytics tools enable better management of agricultural data, including crop yields, environmental conditions and resource use. This data can be used to optimize farming practices, reduce waste and improve overall efficiency.

Carbon Footprint Tracking: Some blockchain solutions incorporate carbon footprint tracking mechanisms to monitor and offset the environmental impact of agricultural activities. By reporting emissions data and implementing carbon reduction initiatives, farmers can reduce their environmental footprint and contribute to climate change mitigation efforts.

Tokenization of Agricultural Assets: Tokenization enables fractional ownership of agricultural assets such as farmland or crops, allowing investors to directly participate in sustainable farming practices. Blockchain-based platforms facilitate transparent investment opportunities in agriculture, fostering sustainable development.

Figure 2: The latest developments related to blockchain applications in sustainable farming practices

Blockchain integration for organic farming

Blockchain integration is recognized to raise organic farming standards by providing a transparent and immutable record of compliance with farming practices, certifications and organic regulations. Through blockchain-enabled platforms, stakeholders can verify the authenticity of organic claims, track the origin of organic products, and ensure compliance with organic standards throughout the supply chain (Khatoon *et al.*, 2019). Smart contracts embedded in blockchain systems can automate certification processes, streamline audits, and improve trust between consumers, retailers, and certification bodies. Blockchain integration into organic farming continues to evolve, offering improved transparency, trust and sustainability in organic food supply chains (Kamilaris *et al.*, 2019; Ahmadi Kaliji and Pakseresht, 2023).

Blockchain can be used to securely store organic certification data, including farm practices, soil health and compliance with organic standards. This ensures transparency and authenticity throughout the organic farming process, reducing the risk of fraud and mislabeling (Tegeltija *et al.*, 2022). Similarly, Blockchain enables the tracking of organic products from farm to fork, providing consumers with real-time information on the origin, production methods and transportation of organic goods. This level of traceability increases trust and confidence in organic food products (Lin *et al.*, 2021). Correspondingly, blockchain-based decentralized markets connect organic farmers directly with consumers, eliminating middlemen and ensuring fair prices for producers and consumers. Smart contracts facilitate transparent transactions and enable automatic payments based on predefined conditions (Luo *et al.*, 2019). Blockchain platforms foster collaboration among organic farmers, researchers and stakeholders by securely sharing agricultural data, best practices and research findings. This will facilitate knowledge sharing and innovation in organic farming methods, thereby improving productivity and sustainability (Kochupillai *et al.*, 2021).

By integrating blockchain technology, organic food supply chains can achieve greater efficiency and resilience. Real-time monitoring of inventory levels, transportation routes, and storage conditions helps minimize waste, reduce spoilage, and optimize distribution processes (Saurabh and Dey, 2021). Blockchain-powered apps and platforms give consumers access to detailed information about organic farming practices, environmental impact assessments and nutritional benefits. This creates greater consumer awareness and promotes informed choices regarding organic food consumption (Menon and Jain, 2021). Some blockchain solutions incorporate carbon footprint tracking and offset mechanisms to quantify and minimize the environmental impact of organic farming activities. By encouraging sustainable practices and carbon sequestration initiatives, blockchain contributes to reducing the carbon footprint of organic agriculture (Rani *et al.*, 2024). Blockchain facilitates regulatory compliance by maintaining an incorruptible record of organic certification documents, audits and inspections. This streamlines the certification process and ensures compliance with organic standards, increasing the credibility of organic farming practices (Gould *et al.*, 2019).

Enhancing conservation efforts with blockchain traceability

Blockchain traceability has emerged as a powerful tool to enhance conservation efforts, particularly in the context of medicinal plant sourcing, harvesting and trade. That is, Blockchain technology allows for the creation of transparent and immutable records of every transaction or activity in the medicinal plant supply chain (Kochupillai *et al.*, 2021). This securely records the entire journey of these plants from harvest to distribution and minimizes the risk of fraud, mismanagement or unsustainable practices. Similarly, through blockchain traceability, stakeholders can monitor the sustainability of medicinal plant resources in real time. By looking at factors such as harvesting practices, quantities extracted, and geographic locations, conservationists can assess impacts on ecosystems and biodiversity, identify areas of concern, and implement targeted conservation interventions (Hamilton, 2004; Galvez *et al.*, 2018). Blockchain-enabled platforms, on the other hand, facilitates data sharing and collaboration among stakeholders engaged in conservation efforts (Kochupillai *et al.*, 2021). Researchers, government agencies, non-profit organizations, and local communities can securely share information about plant populations, habitat conditions, and conservation initiatives, and collaborate and share knowledge. Blockchain-based incentive mechanisms such as tokenization and smart contracts support sustainable practices and can encourage habitat restoration efforts (Mendoza Tovar, 2023). For example, farmers or communities that engage in responsible harvesting or habitat conservation can be rewarded with tokens or financial incentives, promoting long-term conservation goals.

Blockchain can streamline the certification process for sustainably harvested medicinal plants by securely recording certification documents and compliance data in a decentralized ledger. This improves confidence in the authenticity and sustainability of certified products, facilitates access to premium markets and fair compensation for responsible producers (Dutta *et al.*, 2020). Moreover, Blockchain traceability enables consumers to make informed choices by providing access to detailed information on medicinal plant-related provenance and sustainable practices. By promoting transparency and awareness, Blockchain empowers consumers to support conservation-friendly products and contribute to biodiversity conservation efforts (Loundou, 2008; Mir *et al.*, 2021).

Propagating medicinal plants: blockchain-enabled approaches

Propagation of medicinal plants has been identified as playing a crucial role in the field of health. The process provides ingredients for various medicines, herbal remedies and supplements and this process is often fraught with challenges, including issues related to transparency, traceability and management of intellectual property rights (Hossain *et al.*, 2022). In recent years, blockchain technology has emerged as a potential solution to these challenges, offering many benefits to researchers, nurseries and conservationists involved in medicinal plant propagation (Wani *et al*., 2023).

A primary advantage of blockchain technology in medicinal plant propagation is its ability to provide transparent and verifiable records of plant genetics, propagation methods, and germplasm transfer. By digitizing plant pedigrees and propagation data on blockchain platforms, stakeholders can ensure the integrity and authenticity of information related to the origin and history of medicinal plant varieties (Bamakan *et al*., 2021). This transparency not only improves trust and accountability but also facilitates compliance with regulatory requirements and quality assurance standards. Similarly, Blockchain technology facilitates improved traceability throughout the medicinal plant supply chain and enables stakeholders to trace the lineage of plant varieties from their origins to their current state. This traceability is essential to verify the authenticity and quality of medicinal plant products, as well as to ensure compliance with legal and ethical standards (Saha *et al*., 2018; Balekundri and Mannur, 2020). By recording transactions and updates on the blockchain, stakeholders can reduce the risks associated with counterfeit products and supply chain disruptions, thereby protecting the interests of consumers and industry stakeholders alike (de Boissieu *et al*., 2021).

Blockchain-enabled approaches streamline breeding programs by facilitating data exchange and collaboration between researchers and breeders. By digitizing plant pedigrees, genetic information and performance evaluations on blockchain platforms, breeders can gain valuable insights into the traits and characteristics of different plant varieties, accelerating the development of new and improved cultivars with improved medicinal properties. This collaborative approach not only fosters innovation, but also maximizes the efficiency and effectiveness of breeding efforts while ultimately benefiting the entire medicinal plant industry (Camacho-Henriquez *et al*., 2015; Bakarich *et al*., 2020). Maintaining genetic diversity is critical to the long-term sustainability of medicinal plant populations, as it ensures resilience to environmental changes and disease outbreaks. Blockchain technology can help conservationists more effectively monitor and manage germplasm collections, ensuring the preservation of diverse genetic resources for future generations (Pathirana and Carimi, 2022). By recording germline exchanges, conservation efforts and breeding initiatives on the blockchain, stakeholders can track the movement of genetic material and identify priority areas for conservation efforts, thereby contributing to the preservation of biodiversity and ecosystem health. Smart contracts are a key component of blockchain technology, and these self-executing contracts fairly compensate breeders and researchers for their contributions and facilitate licensing agreements and collaborations (Wang *et al*., 2019). By eliminating intermediaries and streamlining administrative processes, smart contracts improve the efficiency and transparency of intellectual property management, thereby encouraging innovation and investment in medicinal plant research and development (Bamakan *et al*., 2021; Wang *et al*., 2021).

Case studies and examples of blockchain implementation in medicinal plant industries

With the advancement of information technology, a transparent blockchain platform called HerBChain has been developed to improve the quality assurance of medicines. It aims to minimize the damage to recorded data by using blockchain technology. HerBCchain serves as a platform to document six critical stages of herbal product production and distribution, including plantation sites, traditional Chinese medicine processing facilities, manufacturers, laboratories, distributors, and retailers (Wang *et al*., 2021). The use of blockchain as a distributed ledger technology in the form of a decentralized transaction database for food quality and value is encrypted and secured by a consensus mechanism (Sharma *et al*., 2023). Sensors are used to measure various indicators related to a product and record information at every stage of the supply chain. Distributors and retailers use the VeChain chip to confirm whether a product is authentic or not, and customers interact with the chip, tag, or code to retrieve information. By doing this, information about how products are handled can be accessed (Kshetri, 2023). VeChain, a blockchain platform, has been used to trace and verify the authenticity of wine products, and this application can be extended to the medicinal plant industry, allowing consumers to track the journey of medicinal plants from cultivation to consumption (Xiao *et al*., 2024). On the other hand, consumers can confirm that the products they purchased are legal and handled properly. When consumers scan a QR code, they can get detailed information about the product. Likewise, IBM Food Trust partnered with Walmart to create a blockchain-based food tracking system. Initially focused on food products, this platform demonstrates the potential for similar initiatives in the medicinal plants sector and ensures transparency and quality assurance (Yiannas, 2018). Walmart and IBM Build Decentralized Food Delivery Ecosystem Blockchain Technology Based on Food Tracking System Based on Hyper Ledger Fabric Tested by Tracking Mangoes Sold in Walmart's US Stores and Pork Sold in Chinese Stores (Ahamed *et al*., 2022). Due to its success, this method has been applied to other food and medicinal plants as well.

IBM Food Trust is a collaborative network of growers, processors, wholesalers, distributors, manufacturers, retailers, and others, improving visibility and accountability across the food supply chain. Built on the IBM Blockchain, this solution connects participants through permissioned, immutable, and shared records, transaction data, processing details, and more (Kirbac and Ergenc, 2021). From farmer to processor to retailer to consumer, IBM Food Trust uses trust to build transparency. The blockchain solution works to ensure that a transparent and scalable food system is enabled. With capabilities to enable safer food, longer product shelf life, less wastage, faster discovery, and better access to shared information, the IBM Food Trust delivers greater value in the safety of herbal products as it empowers it to meet the new standard for food transparency and trust. The solution gives authorized users instant access to actionable food supply chain data and delivers safe food from farm to store and ultimately to the consumer. The complete history of any food item and its current location and the information it contains (i.e., certifications, test data, temperature data) can be easily retrieved in seconds. Correspondingly, IBM Food Trust integrates supply chain modules with blockchain core functions to deliver business value to the food and herbal medicine ecosystem through a combination of governance, standards, interoperability, and technology. This ensures the freshness of food and herbal medicines as well as product quality, minimizes wastage and product loss, optimizes the ecosystem, and ensures sustainability. This condition is essential in medicinal plants because it directly contributes to the preservation of human lives (Howson, 2020; Nuseir, 2021). Additionally, Farm2Kitchen is a food discovery platform used to track the movement of food products from farm to table. It enables the operation of organic food warehouses and distribution of food to processed food manufacturers, improving food safety. It is also important for agricultural growth, food security, and economic development, and can be used to improve the safety and quality of medicinal plants. Therefore, the future of sustainable agricultural growth and food security worldwide is moving towards a new path of medicinal herbal production (Zhang *et al*., 2021; Kayikci *et al*., 2022).

Challenges and limitations of blockchain integration in medicinal plant supply chains

Although the integration of blockchain technology into the medicinal plant supply chain has been identified as a potential solution to improve transparency, traceability and quality assurance, the implementation of blockchain in such complex ecosystems has identified several challenges and limitations that require careful consideration.

One of the foremost challenges in integrating blockchain technology is the significant cost associated with its implementation. Although blockchain offers significant benefits, the required upfront investment in development, infrastructure, and maintenance is a challenge, especially for small-scale manufacturers or stakeholders in resource-constrained settings. Thus, it is important to carefully evaluate the cost-effectiveness of blockchain solutions against the potential benefits they offer (Pandey and Litoriya, 2020). Integrating blockchain into existing supply chain systems is a complex process requiring technical expertise and resources, further complicating the process of integrating blockchain interoperability with legacy systems and standards across multiple stakeholders. Overcoming these technical challenges requires strong planning, collaboration, and investment in IT infrastructure, and the situation can be daunting, especially for stakeholders with limited technical capabilities. (Al-Rakhami and Al-Mashari, 2022). While blockchain technology inherently offers enhanced security through its decentralized and immutable nature, it can raise data privacy and cybersecurity issues. Unauthorized access to sensitive information stored on the blockchain can jeopardize supply chain integrity and undermine consumer trust. Addressing these issues requires strong encryption mechanisms, strict access controls, and compliance with data protection regulations to protect confidential information (Saha *et al.*, 2024).

As transaction volume increases, scalability remains a significant challenge for blockchain networks, especially public ones. The processing capacity of blockchain platforms can be limited, leading to network congestion, transaction processing delays, and reduced supply chain efficiency. As demand for real-time transaction processing grows, issues of scalability must be addressed through the development of scalable blockchain solutions or alternative technologies to ensure seamless operation of supply chains (Jabbar *et al.*, 2021). Navigating regulatory frameworks and compliance requirements poses another challenge in integrating blockchain technology into medicinal plant supply chains. Regulatory uncertainty surrounding the use of blockchain, along with evolving standards and guidelines, creates ambiguity for stakeholders looking to implement blockchain solutions (Nikolakis *et al.*, 2018). Ensuring compliance with existing regulations and adapting to regulatory changes requires ongoing monitoring, legal expertise and collaboration with regulatory authorities to minimize legal risks and ensure regulatory compliance. Despite the potential benefits of blockchain technology, limited awareness and understanding of its applications in the medicinal plant industry is hindering adoption. Stakeholders may lack the knowledge or incentives to invest in blockchain solutions, thereby hindering widespread adoption. Educating stakeholders about the benefits of blockchain, addressing misconceptions, and fostering a supportive ecosystem for blockchain innovation are essential steps to promote adoption and overcome resistance to change (Tanwar *et al.*, 2022). Another issue to consider is the environmental sustainability of blockchain technology, as some blockchain networks, especially those based on proof-of-work consensus mechanisms, consume significant amounts of energy, creating large carbon footprints. As environmental sustainability becomes more and more important, stakeholders should explore energy-efficient alternatives or implement measures to reduce the environmental impact of blocking processes (Shibu *et al.*, 2024). Similarly, achieving interoperability between different blockchain platforms and systems used by different stakeholders is critical for seamless data exchange and transparency in supply chains. However, the lack of standardized protocols and interoperability standards poses a significant challenge to achieving seamless integration. Efforts are needed to develop interoperable blockchain solutions and establish industry-wide standards to facilitate data interoperability and improve the efficiency of blockchain integration in medicinal plant supply chains (Jabbar *et al.*, 2021). Another issue to consider is the environmental sustainability of blockchain technology, as some blockchain networks, especially those based on proof-of-work consensus mechanisms, consume significant amounts of energy, creating large carbon footprints. As environmental sustainability becomes more and more important, stakeholders should explore energy-efficient alternatives or implement measures to reduce the environmental impact of blocking processes (Shibu *et al.*, 2024). Finally, blockchain technology offers tremendous support for improving transparency, traceability, and quality assurance in medicinal plant supply chains despite various challenges and limitations through blockchain technology. By acknowledging these challenges and developing scalable, cost-effective and secure blockchain solutions, stakeholders can overcome barriers and realize the transformative benefits of blockchain in ensuring the integrity and security of medicinal plant supply chains (Dutta *et al.*, 2020; Sunny *et al.*, 2020; Lv *et al.*, 2023).

Future directions and opportunities for blockchain in sustainable medicinal plant management

Blockchain technology has the potential to optimize medicinal plant supply chains by reducing inefficiencies, mitigating risks, and increasing transparency. Smart contracts can also automate payment processes and enforce fair trade practices in medicinal plant supply chains. By integrating smart contracts with blockchain platforms, stakeholders can ensure timely and transparent transactions, empower farmers, and promote fair value distribution. Similarly, direct interactions between producers and consumers can be fostered, promoting community resilience and socio-economic development. Additionally, blockchain integration with Internet of Things (IoT) devices enables real-time monitoring of environmental conditions such as soil moisture levels and temperature in medicinal plant cultivation. This integration improves data accuracy and enables proactive decision-making to optimize plant health and yield. Correspondingly, blockchain-based decentralized marketplaces facilitate direct trade between herbal producers and consumers while reducing transaction costs by bypassing intermediaries. These platforms empower small-scale farmers, promote market access, and foster community participation in sustainable agricultural practices. Furthermore, blockchain-enabled platforms can facilitate the evaluation of ecosystem services provided by medicinal plants. By sequestering carbon, improving soil fertility, conserving biodiversity, codifying ecosystem services, and creating incentive mechanisms, stakeholders can promote sustainable land management practices and benefit conservation efforts in medicinal plant ecosystems.

CONCLUSIONS

In conclusion, the integration of blockchain technology into the medicinal plant and organic farming industries offers a transformative solution to address key challenges such as traceability, transparency, and sustainability. By leveraging blockchain's immutable and transparent ledger, stakeholders in these industries can ensure the authenticity, quality, and ethical sourcing of medicinal plants and organic products, thus fostering trust among consumers and enhancing industry credibility. Blockchain's applications in supply chain traceability, provenance verification, smart contracts, asset tokenization, and data management enable stakeholders to monitor and optimize agricultural activities while promoting fair trade practices and sustainable cultivation methods. Through blockchain integration, organic farming standards are elevated, ensuring compliance with regulations and enhancing consumer confidence in organic products. Furthermore, blockchain facilitates collaboration among farmers, suppliers, distributors, and consumers, creating a transparent ecosystem that promotes knowledge sharing, innovation, and sustainable development across the agricultural value chain. Additionally, blockchain's role in carbon footprint tracking and regulatory compliance enhances environmental stewardship and industry accountability. As consumer demand for transparency and sustainability continues to rise, the adoption of blockchain technology in the medicinal plant and organic farming industries not only meets these expectations but also drives positive change towards a more ethical, resilient, and environmentally conscious agricultural sector. Thus, embracing blockchain represents a crucial step towards achieving a more sustainable and equitable future for medicinal plant cultivation and organic farming worldwide. The integration of blockchain technology in medicinal plant industries presents a promising pathway towards enhancing conservation efforts, sustainable management, and transparency in supply chains. Blockchain's ability to create transparent and immutable records enables stakeholders to monitor and trace the journey of medicinal plants from harvest to distribution, thereby reducing the risks of fraud, mismanagement, and unsustainable practices.

By leveraging blockchain traceability, conservationists can assess the sustainability of medicinal plant resources in real-time, identify areas of concern, and implement targeted interventions to protect biodiversity and ecosystems. Collaboration among stakeholders is facilitated through blockchain-enabled platforms, fostering data sharing, and incentivizing sustainable practices such as habitat restoration. Furthermore, blockchain streamlines the certification process for sustainably harvested medicinal plants, improving consumer confidence in certified products and facilitating access to premium markets. Consumers can make informed choices by accessing detailed information on plant provenance and sustainable practices, empowering them to support conservation-friendly products. In the propagation of medicinal plants, blockchain enhances transparency and traceability, ensuring the authenticity of plant genetics and facilitating collaboration among researchers and breeders. Smart contracts automate administrative processes and fairly compensate stakeholders, fostering innovation and investment in medicinal plant research and development. Despite challenges such as implementation costs, technical complexities, and regulatory uncertainties, blockchain offers transformative opportunities for sustainable management and conservation of medicinal plant resources. With ongoing innovation and collaboration, stakeholders can overcome barriers and realize the full potential of blockchain in ensuring the integrity, security, and sustainability of medicinal plant supply chains. Overall, blockchain technology represents a powerful tool for promoting biodiversity conservation, sustainable management, and ethical sourcing practices in the medicinal plant industry, contributing to a more resilient and environmentally conscious future for global herbal medicine production and consumption.

REFERENCES

Ahamed, N.N. and Vignesh, R. (2022). Smart agriculture and food industry with blockchain and artificial intelligence. Journal of Computer Science. 18(1), 1-17.

Ahmadi Kaliji, S. and Pakseresht, A. (2023). Applying Blockchain Technology for Food Traceability pp. 1-10. In: Zhang, Q. (Ed.), Encyclopedia of Smart Agriculture Technologies. Springer, Cham.

Al-Rakhami, M. and Al-Mashari, M. (2022). Interoperability approaches of blockchain technology for supply chain systems. Business Process Management Journal. 28(5/6), 1251-1276.

Bakarich, K.M., Castonguay, J.J. and O'Brien, P.E. (2020). The use of blockchains to enhance sustainability reporting and assurance. Accounting Perspectives. 19(4), 389-412.

Balekundri, A. and Mannur, V. (2020). Quality control of the traditional herbs and herbal products: A review. Future Journal of Pharmaceutical Sciences. 6, 1-9.

Bamakan, S.M.H., Moghaddam, S.G. and Manshadi, S.D. (2021). Blockchain-enabled pharmaceutical cold chain: Applications, key challenges, and future trends. Journal of Cleaner Production. 302, 127021.

Bargshady, G., Zahraee, S.M., Ahmadi, M. and Parto, A. (2016). The effect of information technology on the agility of the supply chain in the Iranian power plant industry. Journal of Manufacturing Technology Management. 27(3), 427-442.

Beck-O'Brien, M. and Bringezu, S. (2021). Biodiversity monitoring in long-distance food supply chains: Tools, gaps and needs to meet business requirements and sustainability goals. Sustainability. 13(15), 8536.

Brown, A.C. (2017). An overview of herb and dietary supplement efficacy, safety and government regulations in the United States with suggested improvements. Part 1 of 5 series. Food and Chemical Toxicology. 107, 449-471.

Camacho-Henriquez, A.; Kraemer, F.; Galluzzi, G.; Haan, S. de.; Jäger, M.; Christinck, A. (2015). Decentralized collaborative plant breeding for utilization and conservation of neglected and underutilized crop genetic resources pp. 25-61. In: Al-Khayri, J., Jain, S.M. and Johnson, D.V. (Ed.), Advances in plant breeding strategies: Breeding, biotechnology and molecular tools. Springer International Publishing, Switzerland.

Carlisle, L. (2022). Healing grounds: climate, justice, and the deep roots of regenerative farming. Island Press.

De Boissieu, E., Kondrateva, G., Baudier, P. and Ammi, C. (2021). The use of blockchain in the luxury industry: supply chains and the traceability of goods. Journal of Enterprise Information Management. 34(5), 1318-1338.

Demestichas, K., Peppes, N., Alexakis, T. and Adamopoulou, E. (2020). Blockchain in agriculture traceability systems: A review. Applied Sciences. 10(12), 4113.

Dessart, F.J., Barreiro-Hurlé, J. and Van Bavel, R. (2019). Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. European Review of Agricultural Economics. 46(3), 417-471.

Dutta, P., Choi, T.M., Somani, S. and Butala, R. (2020). Blockchain technology in supply chain operations: Applications, challenges and research opportunities. Transportation Research Part e: Logistics and Transportation Review. 142, 102067.

Ehrlich, P.R. (2002). Human natures, nature conservation, and environmental ethics: Cultural evolution is required, in both the scientific community and the public at large, to improve significantly the now inadequate response of society to the human predicament. BioScience. 52(1), 31-43.

Frey, D. (2011). Bioshelter market garden: a permaculture farm. New Society Publishers.

Galvez, J.F., Mejuto, J.C. and Simal-Gandara, J. (2018). Future challenges on the use of blockchain for food traceability analysis. TrAC Trends in Analytical Chemistry. 107, 222-232.

Gardner, T.A., Benzie, M., Börner, J., Dawkins, E., Fick, S., Garrett, R. and Wolvekamp, P. (2019). Transparency and sustainability in global commodity supply chains. World Development. 121, 163-177.

Ge, L., Brewster, C., Spek, J., Smeenk, A., Top, J., Van Diepen, F. and de Wildt, M. D.R. (2017). Blockchain for agriculture and food: Findings from the pilot study (No. 2017-112). Wageningen Economic Research.

Gould, D., Compagnoni, A. and Lembo, G. (2019). Organic Aquaculture: Principles, Standards and Certification pp 1-22. In: Lembo, G., Mente, E. (Ed.), Organic Aquaculture. Springer, Cham.

Gurzawska, A. (2020). Towards responsible and sustainable supply chains–innovation, multi-stakeholder approach and governance. Philosophy of Management. 19(3), 267-295.

Hamilton, A.C. (2004). Medicinal plants, conservation and livelihoods. Biodiversity and Conservation. 13, 1477-1517.

Hastig, G.M. and Sodhi, M.S. (2020). Blockchain for supply chain traceability: Business requirements and critical success factors. Production and Operations Management. 29(4), 935-954.

Hossain, C.M., Gera, M. and Ali, K.A. (2022). Current status and challenges of herbal drug development and regulatory aspect: A global perspective. Asian Journal Pharm Clinical Research. 15(12), 31-41.

Howson, P. (2020). Building trust and equity in marine conservation and fisheries supply chain management with blockchain. Marine Policy. 115, 103873.

Iqbal, R. and Butt, T.A. (2020). Safe farming as a service of blockchain-based supply chain management for improved transparency. Cluster Computing. 23, 2139-2150.

Jabbar, S., Lloyd, H., Hammoudeh, M., Adebisi, B. and Raza, U. (2021). Blockchain-enabled supply chain: analysis, challenges, and future directions. Multimedia Systems. 27, 787-806.

Kamilaris, A., Fonts, A. and Prenafeta-Boldύ, F.X. (2019). The rise of blockchain technology in agriculture and food supply chains. Trends in Food Science and Technology. 91, 640-652.

Kayikci, Y., Subramanian, N., Dora, M. and Bhatia, M.S. (2022). Food supply chain in the era of Industry 4.0: Blockchain technology implementation opportunities and impediments from the perspective of people, process, performance, and technology. Production Planning and Control. 33(2-3), 301-321.

Khatoon, A., Verma, P., Southernwood, J., Massey, B. and Corcoran, P. (2019). Blockchain in energy efficiency: Potential applications and benefits. Energies. 12(17), 3317.

Kirbac, G. and Ergenc, E. (2021). The effect of the blockchain technology on service companies and food retailers: An overview of the blockchain use cases and applications pp 100. In: Cobanoglu, C. and Corte, V.D. (Ed.), Advances in Global Services and Retail Management: Volume 2. University of South Florida (USF) M3 Publishing, USA.

Kiruba, K., Hemalatha, P., Manikandan, J., Madhin, M. and Mohan, R.S. (2021). Revolutionizing secure commercialization in agriculture using blockchain technology. 2021 International Conference on System, Computation, Automation and Networking (ICSCAN). IEEE. 1-6.

Kochupillai, M., Gallersdörfer, U., Köninger, J. and Beck, R. (2021). Incentivizing research and innovation with agrobiodiversity conserved in situ: Possibilities and limitations of a blockchain-based solution. Journal of Cleaner Production. 309, 127155.

Kshetri, N. (2023). Blockchains with Chinese characteristics. pp 83-111. In: Blockchain in the Global South: Opportunities and Challenges for Businesses and Societies. Springer Nature, Cham, Switzerland.

Lin, W., Huang, X., Fang, H., Wang, V., Hua, Y., Wang, J. and Yau, L. (2020). Blockchain technology in current agricultural systems: from techniques to applications. IEEE Access. 8, 143920-143937.

Lin, X., Chang, S.C., Chou, T.H., Chen, S.C. and Ruangkanjanases, A. (2021). Consumers' intention to adopt blockchain food traceability technology towards organic food products. International Journal of Environmental Research and Public Health. 18(3), 912.

Liu, C., Zuo, Z., Xu, F. and Wang, Y. (2023). Authentication of herbal medicines based on modern analytical technology combined with chemometrics approach: A review. Critical Reviews in Analytical Chemistry. 53(7), 1393-1418.

Loundou, P.M. (2008). Medicinal plant trade and opportunities for sustainable management in the Cape Peninsula, South Africa, Doctoral dissertation, Stellenbosch: Stellenbosch University.

Luo, H., Das, M., Wang, J. and Cheng, J.C. (2019). Construction payment automation through smart contract-based blockchain framework. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction. IAARC Publications. 36, 1254-1260.

Lv, G., Song, C., Xu, P., Qi, Z., Song, H. and Liu, Y. (2023). Blockchain-Based Traceability for Agricultural Products: A Systematic Literature Review. Agriculture. 13(9), 1757.

Martin, J.L., Maris, V. and Simberloff, D.S. (2016). The need to respect nature and its limits challenges society and conservation science. Proceedings of the National Academy of Sciences. 113(22), 6105-6112.

Mehannaoui, R., Mouss, K.N. and Aksa, K. (2023). IoT-based food traceability system: Architecture, technologies, applications, and future trends. Food Control. 145, 109409.

Mendoza Tovar, E. (2023). Blockchain for environmental sustainability, Doctoral dissertation, Faculty of Economics and Administration, Masaryk University.

Menon, S. and Jain, K. (2021). Blockchain technology for transparency in agri-food supply chain: Use cases, limitations, and future directions. IEEE Transactions on Engineering Management. 71, 106-120.

Mir, T.A., Jan, M., Khare, R.K. and Bhat, M.H. (2021). Medicinal Plant Resources: Threat to Its Biodiversity and Conservation Strategies pp 717-204. In: Aftab, T. and Hakeem, K.R. (Ed.), Medicinal and Aromatic Plants. Springer, Cham.

Nafiu, M.O., Hamid, A.A., Muritala, H.F. and Adeyemi, S.B. (2017). Preparation, standardization, and quality control of medicinal plants in Africa. Medicinal Spices and Vegetables from Africa. 171-204.

Ndawonde, B.G. (2015). Education for sustainable development of medicinal plant sellers-challenges in relation to marketing, sales, storage and conservation, Doctoral dissertation, University of Zululand.

Nikolakis, W., John, L. and Krishnan, H. (2018). How blockchain can shape sustainable global value chains: An evidence, verifiability, and enforceability (EVE) framework. Sustainability. 10(11), 3926.

Nuseir, M.T. (2021). Potential impacts of blockchain technology on business practices of bricks and mortar (B and M) grocery stores. Business Process Management Journal, 27(4), 1256-1274.

Obahiagbon, E.G. and Ogwu, M.C. (2024). The Nexus of Business, Sustainability, and Herbal Medicine pp 1-42. In: Izah, S.C., Ogwu, M.C., Akram, M. (Ed.), Herbal Medicine Phytochemistry. Reference Series in Phytochemistry. Springer, Cham.

Pandey, P. and Litoriya, R. (2020). Implementing healthcare services on a large scale: challenges and remedies based on blockchain technology. Health Policy and Technology. 9(1), 69-78.

Pathirana, R. and Carimi, F. (2022). Management and utilization of plant genetic resources for a sustainable agriculture. Plants. 11(15), 2038.

Rani, P., Sharma, P. and Gupta, I. (2024). Toward a greener future: A survey on sustainable blockchain applications and impact. Journal of Environmental Management. 354, 120273.

Rejeb, A., Keogh, J.G. and Treiblmaier, H. (2019). Leveraging the internet of things and blockchain technology in supply chain management. Future Internet. 11(7), 161.

Saha, A., Raut, R.D. and Kumar, M. (2024). Leveraging blockchain technology to combat food fraud in the agri-food supply chain. International Journal of Food Science and Technology. 59(5), 3469-3477.

Saha, S., Mandal, A. and Dutta, A. (2018). Good agricultural practices: requirement for the production of quality herbal medicines pp 607-631. In: Subhash, C., Mandal, V., Konishi, T. (Ed.), Natural Products and Drug Discovery. Elsevier.

Salah, K., Nizamuddin, N., Jayaraman, R. and Omar, M. (2019). Blockchain-based soybean traceability in agricultural supply chain. IEEE Access. 7, 73295-73305.

Salmi, A., Quarshie, A.M., Scott-Kennel, J. and Kähkönen, A.K. (2023). Biodiversity management: A supply chain practice view. Journal of Purchasing and Supply Management. 29(4), 100865.

Sanghera, G.S., Bhatia, D. and Thind, K.S. (2015). Access and Benefit Sharing on the Use of Indigenous Traditional Knowledge pp 163-181. In: Salgotra, R., Gupta, B. (Ed.), Plant Genetic Resources and Traditional Knowledge for Food Security. Springer, Singapore.

Saurabh, S. and Dey, K. (2021). Blockchain technology adoption, architecture, and sustainable agri-food supply chains. Journal of Cleaner Production. 284, 124731.

Sharma, V., Jamwal, A., & Agrawal, R. (2023). Framework for Assessing Trust in the Use of Blockchain Technology in Agrifood Supply Chains. Engineering Proceedings. 40(1), 7.

Shibu, N.S., Devidas, A.R., Balamurugan, S., Ponnekanti, S. and Ramesh, M.V. (2024). Optimising Microgrid Resilience: Integrating IoT, Blockchain, and Smart Contracts for Power Outage Management. IEEE Access. 12, 18782-18803.

Sunny, J., Undralla, N. and Pillai, V.M. (2020). Supply chain transparency through blockchain-based traceability: An overview with demonstration. Computers and Industrial Engineering. 150, 106895.

Tanwar, S., Parmar, A., Kumari, A., Jadav, N.K., Hong, W.C. and Sharma, R. (2022). Blockchain adoption to secure the food industry: Opportunities and challenges. Sustainability. 14(12), 7036.

Tegeltija, S., Dejanović, S., Feng, H., Stankovski, S., Ostojić, G., Kučević, D. and Marjanović, J. (2022). Blockchain framework for certification of organic agriculture production. Sustainability. 14(19), 11823.

Tian, F. (2017). A supply chain traceability system for food safety based on HACCP, blockchain and Internet of things. 2017 International Conference on Service Systems and Service Management. IEEE. 1-6.

Torky, M. and Hassanein, A.E. (2020). Integrating blockchain and the internet of things in precision agriculture: Analysis, opportunities, and challenges. Computers and Electronics in Agriculture. 178, 105476.

Tripathy, V., Basak, B.B., Varghese, T.S. and Saha, A. (2015). Residues and contaminants in medicinal herbs-A review. Phytochemistry Letters. 14, 67-78.

Vian, Taryn and Kohler, Jillian. (2016). Medicines Transparency Alliance (MeTA): Pathways to Transparency, Accountability, and Access: Cross-Case Analysis and Review of Phase II. 10.13140/RG.2.1.2468.6326.

Wang, Y., Han, J.H. and Beynon-Davies, P. (2019). Understanding blockchain technology for future supply chains: a systematic literature review and research agenda. Supply Chain Management: An International Journal. 24(1), 62-84.

Wang, Z., Wang, L., Xiao, F.A., Chen, Q., Lu, L. and Hong, J. (2021). A traditional Chinese medicine traceability system based on lightweight blockchain. Journal of Medical Internet Research. 23(6), 25946.

Wani, M.A., Din, A., Nazki, I.T., Rehman, T.U., Al-Khayri, J.M., Jain, S.M. and Mushtaq, M. (2023). Navigating the future: exploring technological advancements and emerging trends in the sustainable ornamental industry. Frontiers in Environmental Science. 11, 1188643.

Wognum, P.N., Bremmers, H., Trienekens, J.H., Van Der Vorst, J.G. and Bloemhof, J.M. (2011). Systems for sustainability and transparency of food supply chains–Current status and challenges. Advanced Engineering Informatics. 25(1), 65-76.

Xiao, G., Samian, N., Faizal, M.F.M., As'ad, M.A.Z.M., Fadzil, M.F.M., Abdullah, A. and Hermadi, I. (2024). A framework for blockchain and internet of things integration in improving food security in the food supply chain. Journal of Advanced Research in Applied Sciences and Engineering Technology. 34(1), 24-37.

Yang, X., Li, M., Yu, H., Wang, M., Xu, D. and Sun, C. (2021). A trusted blockchain-based traceability system for fruit and vegetable agricultural products. IEEE Access. 9, 36282-36293.

Yiannas, F. (2018). A new era of food transparency powered by blockchain. Innovations: Technology, Governance, Globalization. 12(1-2), 46-56.

Zhang, Q., Zhang, L., Li, Y. and Ye, M. (2021). Drug packaging management based on the effect of medical images on the intracellular polysaccharide synthesis and antivertigo activity of phalaenopsis. Journal of Healthcare Engineering. 2021(1), 1-12.