BLOCKCHAIN TECHNOLOGY FOR ENHANCED TRACEABILITY AND SUSTAINABILITY OF PERSONAL PROTECTIVE EQUIPMENT IN ROMANIAN AGRICULTURE
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TEHNOLOGIA BLOCKCHAIN PENTRU ÎMBUNĂTĂȚIREA TRASABILITĂȚII ȘI SUSTENABILITĂȚII ECHIPAMENTELOR INDIVIDUALE DE PROTECȚIE ÎN AGRICULTURA DIN ROMÂNIA

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ABSTRACT

Blockchain technology provides a secure and transparent method to improve the traceability and sustainability of personal protective equipment (PPE) in Romanian agriculture. By enabling comprehensive monitoring of PPE across its lifecycle, blockchain addresses gaps in safety and compliance. It ensures adherence to safety standards while reducing risks of counterfeit or defective products. However, several challenges hinder adoption. High costs, limited digital infrastructure, and low digital literacy among farmers create significant barriers. Overcoming these requires targeted investments in rural digital infrastructure and training programs designed to enhance stakeholders' skills. Public-private partnerships and pilot projects are essential to demonstrate the technology's benefits and build trust among users. Gradual implementation, supported by collaboration between public and private sectors, can transform Romanian agriculture. Blockchain's integration can lead to better productivity, improved safety, and greater sustainability. This study examines blockchain's potential in PPE management, offering insights into its applications, benefits, and necessary steps for successful adoption in the agricultural sector. Through strategic action, Romanian agriculture can leverage blockchain to achieve safer practices and long-term sustainability.

REZUMAT

Tehnologia blockchain oferă o metodă sigură și transparentă pentru a îmbunătăți trasabilitatea și sustenabilitatea echipamentelor individuale de protecție (EIP) în agricultura din România. Prin monitorizarea cuprinzătoare a EIP pe parcursul ciclului său de viață, blockchain abordează lacunele privind siguranța și conformitatea. Aceasta asigură respectarea standardelor de siguranță, reducând în același timp riscurile de produse contrafăcute sau defecte. Cu toate acestea, mai multe provocări împiedică adoptarea tehnologiei. Costurile ridicate, infrastructura digitală limitată și alfabetizarea digitală scăzută în rândul fermierilor creează bariere semnificative. Depășirea acestora necesită investiții direcționate în infrastructura digitală rurală și programe de formare concepute pentru a îmbunătăți competențele părților interesate. Parteneriatele public-privat și proiectele pilot sunt esențiale pentru a demonstra beneficiile tehnologiei și pentru a construi încrederea utilizatorilor. Implementarea treptată, susținută de colaborarea între sectorul public și cel privat, poate transforma agricultura din România. Integrarea blockchain poate duce la o productivitate mai bună, siguranță îmbunătățită și sustenabilitate sporită. Acest studiu analizează potențialul blockchain în managementul EIP, oferind perspective asupra aplicațiilor, beneficiilor și pașilor necesari pentru o adoptare reușită în sectorul agricol. Prin acțiuni strategice, agricultura românească poate valorifica blockchain pentru a obține practici mai sigure și sustenabilitate pe termen lung.

INTRODUCTION

This research explores blockchain's potential to improve traceability and sustainability for personal protective equipment in Romania's agricultural sector. Blockchain, a secure, decentralized ledger for recording and verifying transactions, offers transparency and environmental benefits. In the context of PPE, it can help ensure compliance with safety standards and improve inventory tracking. Yet, adoption faces challenges: high costs, limited infrastructure, and a lack of expertise *(Sendros et al. 2022, Cuellar and Johnson, 2022)*.

The study reviews relevant literature to outline the background and trends in blockchain applications within agriculture. Expert consultations provide additional insights from professionals in blockchain and agriculture, while hypothetical scenarios suggest possible uses of blockchain for tracking personal protective equipment (PPE). The findings emphasize a balanced approach involving both public and private sector support. Key recommendations include targeted investments in infrastructure, education, and pilot projects to address barriers and promote broader adoption. Overall, blockchain has the potential to drive a more efficient and sustainable agricultural sector in Romania.

Moreover, consumer perceptions significantly impact purchasing behavior, especially in food safety. Research indicates that when consumers better understand product diagnostics, a key cognitive factor, they make more informed choices *(Buaprommee and Polyorat, 2016)*. This perception of safety is influenced by product details and by emotional and cognitive elements. Improving transparency and delivering accurate information helps reduce information asymmetry, fostering consumer confidence and promoting sustainable purchasing.

One of the key advantages of blockchain technology is its ability to create transparency which is made possible through a secure immutable ledger that tracks and validates every single transaction so that there is complete traceability in the supply chain itself. It allows agricultural products to demonstrate adherence to international standards in food safety and environmental protection thereby enabling them to establish consumer trust *(Guna et al., 2023).* Furthermore, apart from being the basis to apply this technology, resource management and information systems also fall under the category of agriculture since blockchain can provide "data transparency" and "transaction traceability" alongside accurate tracking of the products in the entire supply chain leading to unprecedented improvements on product quality and safety *(Westerlund et al., 2021).*

Blockchain technology offers more than just food traceability. It also improves the management of PPE for farmers and agricultural workers. Items such as gloves, masks, eyewear, and protective suits are essential for protecting these workers from exposure to chemicals, dust, noise, and other agricultural risks for safety and health. Through blockchain, PPE can be tracked effectively, ensuring that only quality-assured equipment is available and accessible *(Borah et al., 2020)*. This streamlined monitoring supports better inventory control, cuts down on waste, and encourages sustainable farming practices *(Lin et al., 2020)*.

Blockchain technology use in Romanian agriculture for PPE traceability is in its early stages. High startup costs and inadequate infrastructure in rural areas create adoption challenges. Many farmers lack the skills and resources to work with blockchain, pointing to a need for targeted training. An unclear legal framework also adds uncertainty, discouraging investment and slowing innovation. For success, collaboration among farmers, distributors, regulators, and other stakeholders is essential, with well-planned efforts to address these barriers.

This study examines blockchain's role in enhancing PPE traceability and sustainability in Romanian agriculture. It reviews key literature, gathers insights from local experts, and outlines example pathways for potential implementation. The research addresses critical questions: How can blockchain strengthen PPE traceability and transparency? What advantages might it offer to farmers, equipment manufacturers, and distributors? What challenges could arise in adopting blockchain for PPE management within Romanian agriculture? Through this approach, the study sheds light on the possibilities and obstacles that blockchain technology presents for advancing PPE management.

MATERIALS AND METHODS

In this study, a mixed-methods approach, including a literature review, expert discussions, and the development of hypothetical scenarios, is employed to examine the potential of blockchain technology for enhancing PPE traceability and sustainability in Romania's agricultural sector. This multi-faceted approach aims to uncover blockchain's potential for managing PPE in agriculture, along with the benefits it may offer and the unique challenges associated with its adoption in Romania.

The methodology begins with a comprehensive literature review, drawing from diverse scientific studies, guidance documents, and technical reports published by international organizations and respected

global research institutions, such as the Food and Agriculture Organization *(FAO, 2024)* and the European Agency for Safety and Health at Work *(EU-OSHA, 2024).* This review explores the use of blockchain in agriculture and related sectors for PPE and other essential safety commodities, presenting examples from countries such as the USA, Australia, and the Netherlands. These cases illustrate blockchain's applications in tracing PPE throughout supply chains, thereby helping to ensure compliance with quality standards and reduce counterfeiting risks.

The literature review analyzes best practices and challenges in applying blockchain to improve the traceability and sustainability of PPE in agriculture across different international contexts. For example, in the United States, blockchain technology is used to monitor PPE for agricultural workers, ensuring compliance to federal regulations and supporting worker health *(Wang et al., 2022).* In Australia, it manages the lifecycle of equipment, from production to disposal, promoting recycling and reducing waste (*Zhang and Fröhling, 2024).* Meanwhile, the Netherlands uses blockchain to foster collaboration between manufacturers, distributors, and regulatory bodies, providing full traceability and building trust among stakeholders *(Louis Dreyfus Company, 2018).* Together, these examples offer practical insights for implementing blockchain in Romanian agriculture, emphasizing the importance of traceability and sustainability in PPE management.

Blockchain technology offers specific benefits for Romanian agriculture, especially in the areas of PPE traceability and sustainability. To support this theoretical analysis, the methodology also involved informal discussions with local experts in agriculture and blockchain. In a relaxed setting, these discussions gathered qualitative insights on participants' perceptions, knowledge, and experiences with blockchain in agriculture. Participants, including farmers, cooperative representatives, sustainability consultants, and researchers, focused on blockchain's advantages in PPE management, the challenges in implementation, and the technological readiness of stakeholders. Conversations with local experts in agriculture and blockchain confirmed much of the literature findings and also helped clear up the ambiguity surrounding the Romanian context for applying blockchain in agriculture. Farmers (n=10), agricultural cooperative representatives (n=2), sustainability consultants (n=13), and researchers (n=5) were further consulted in 30 discussions to establish the challenges and practices described here. There is agreement that the application of blockchain to enhance the traceability and control of PPE in Romanian agriculture is valid, but the possibility for large-scale implementation in practice is debated. These discussions revealed practical insights into local needs, identifying both benefits and obstacles in adopting blockchain.

Further exploring blockchain's role, the methodology examines its implementation in PPE management for Romanian agriculture through three hypothetical scenarios: optimistic, moderate, and pessimistic. Based on the literature review and expert discussions, these scenarios capture different levels of public and private sector involvement. Each scenario presents unique implications for blockchain adoption, offering insights into the necessary conditions, as well as potential risks and opportunities.

To support the decision-making process, a flowchart (see Figure 4) was developed. This flowchart maps out key steps and decision points for each scenario, serving as a tool to structure expert discussions and clarify available options and challenges at each stage. By examining different implementation scenarios, the flowchart highlights critical factors for the successful adoption of blockchain in agriculture.

This approach combines theoretical analysis with practical insights and hypothetical scenarios, providing a comprehensive view of innovation in PPE management. The findings lead to recommendations for how blockchain can help create a safer, more efficient, and sustainable agricultural environment in Romania.

RESULTS

The literature highlights blockchain's potential to transform agriculture, particularly in PPE management, by enabling product tracking across the entire lifecycle, from production and distribution to use and recycling. Blockchain's decentralized, secure, and immutable characteristics provide a transparent and reliable means to monitor supply chains, ensuring adherence to safety and quality standards, which is crucial for PPE that protects agricultural workers' health.

By enhancing traceability and transparency, blockchain supports better compliance with PPE standards in agriculture *(Panwar, 2023)*. Blockchain allows farms to effectively monitor PPE supply and usage, thereby improving worker safety and adherence to protection standards. For instance, smart contracts can trigger notifications if essential equipment is not used correctly, increasing safety without the need for physical inspections. However, high implementation costs and data privacy issues present major challenges, especially for smaller farms with limited access to digital skills and infrastructure.

While the benefits are clear, adopting blockchain in Romania faces significant hurdles. The high costs of implementation make it challenging, especially for small and medium-sized farms with limited budgets. Moreover, rural digital infrastructure is often inadequate for blockchain's requirements, such as high-speed internet and advanced data storage. There is also substantial resistance to change; many farmers rely on traditional practices and may be hesitant to adopt new technologies without clear evidence of benefits. Additionally, low digital literacy and limited access to training restrict farmers' ability to understand and use blockchain effectively. These issues underscore the need for financial, infrastructural, and educational support to facilitate blockchain's integration into Romanian agriculture. Romania also lacks the legislation needed to support or regulate blockchain use in agriculture, leaving many potential adopters uncertain and hesitant to invest. While there have been a few local efforts, such as a project in Timiș County exploring blockchain for tracking agricultural products, these initiatives remain isolated and experimental. In southern counties where agriculture is widespread, there's no sign of major projects using blockchain for PPE management. Despite growing interest, the lack of regulatory backing and funding is a key obstacle to broader adoption *(EBSI4RO, 2022).*

Internationally, groups such as the UN's Food and Agriculture Organization (FAO) highlight blockchain's promise for increasing transparency, traceability, and efficiency in agricultural supply chains. However, FAO also points out that significant challenges, such as technology gaps, weak digital infrastructure, and limited political and financial support, continue to restrict its use *(Sylvester, 2019)*. These issues closely mirror those in Romania, where high costs, limited digital infrastructure, and hesitation from farmers make it tough to apply blockchain widely in agriculture.

Despite its potential to enhance traceability and sustainability in agriculture, particularly in managing PPE, several key issues must be addressed to assess blockchain's feasibility and impact. These include significant financial investment, enhancements to digital infrastructure, raising digital literacy among farmers, and developing a supportive legal framework. Without tackling these challenges, blockchain adoption in Romanian agriculture may remain limited, restricting the sector's ability to leverage the full benefits of this technology. This analysis highlights a mix of benefits, challenges, and potential associated with blockchain's role in Romanian agriculture. Supported by literature, the research shows blockchain's potential to increase transparency, efficiency, and safety in agricultural practices, especially in PPE management. Nonetheless, significant obstacles remain, which could limit the technology's broader adoption across Romania.

However, the literature point to significant obstacles. One primary issue is the high cost of implementation. Blockchain systems require substantial investments in hardware, software, and ongoing maintenance, costs that are often prohibitive for small and medium-sized farms with limited budgets. Furthermore, in many rural areas of Romania, the technological infrastructure is lacking. Limited access to high-speed internet and advanced data storage capabilities increases the complexity and cost of blockchain implementation, posing a substantial challenge to its effective deployment across the agricultural sector.

Another significant barrier to blockchain adoption is the lack of education and training. Many farmers in Romania rely on traditional methods and may hesitate to adopt new digital tools without a clear understanding of their benefits. This reluctance is reinforced by limited digital literacy and inadequate access to training resources, which could otherwise help farmers understand and apply blockchain technology. Additionally, the absence of a clear legislative framework creates further complications, adding uncertainty and discouraging investment. The literature underscores the need for regulatory guidelines to support blockchain, while local experts point out that current policies fall short in addressing these challenges.

Public-private partnerships also represent a key opportunity to promote blockchain technology. Such collaborations could leverage the resources and expertise of both sectors to tackle the financial and technical challenges of blockchain adoption. Experts suggest that these partnerships could create a supportive ecosystem by offering funding, infrastructure, and training programs designed for Romanian farmers. Additionally, legislative support at both national and local levels could play a crucial role in fostering blockchain investment. Clear regulatory frameworks and political backing are highlighted in the literature as essential steps for overcoming initial barriers and achieving sustainable integration of blockchain into agricultural practices.

Despite these challenges, the literature reveals opportunities to encourage blockchain adoption in Romanian agriculture. One promising approach is to launch pilot projects that showcase the technology's benefits. Pilot projects could build trust among stakeholders by demonstrating blockchain's effectiveness in a controlled setting. These projects would allow stakeholders to observe blockchain's impact on agricultural practices, identify potential barriers, and refine the implementation process before considering broader adoption. Figure 1 highlights both significant advantages and notable obstacles in implementing blockchain technology for agriculture, particularly in enhancing PPE traceability, data security, and supply chain integrity.

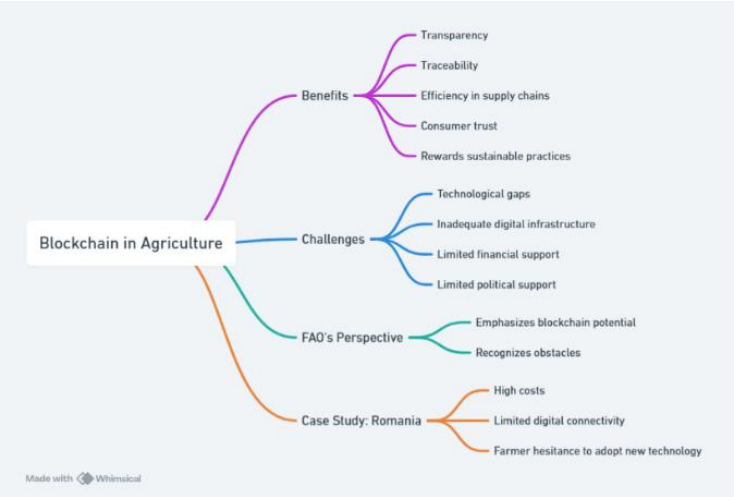

Fig. 1 - Insights from literature on blockchain benefits and challenges in agricultural PPE implementation

This visualization shows a balance of consensus on advantages and obstacles in blockchain implementation for agriculture. There is strong agreement on blockchain's benefits for trust and traceability, while there's equally high consensus on cost and infrastructure as significant challenges.

Approximately 70% of experts surveyed by this research team agree that there is very high potential for blockchain to improve the traceability and transparency of PPE in agriculture. As one expert stated, the transparency, accuracy, and trust levels with blockchain are much higher than traditional agriculture data systems. This demonstrates a perception that blockchain could help keep a supply chain honest, ensure compliance with safety standards, and address issues with defective or counterfeit PPE. Experts noted that blockchain provides a means to create secure, tamper-proof transaction logs across the supply chain to ensure quality and safety standards are maintained, playing a critical role in PPE management. Additionally, 65% of respondents think that trust in agricultural machinery will rise through the use of blockchain, which indicates that, in summary, the general view of blockchain is favorable when it comes to providing truthful and secure information. This confidence in trust factors could allow the agricultural industry, at a larger scale, to accept and adopt new technologies.

Additionally, 65% think the technology would boost trust in agricultural equipment due to its data security and authenticity. Another 60% emphasize that blockchain could facilitate real-time monitoring of PPE, which is important to prevent defective or counterfeit products and make agricultural operations safer. They claim that the ability to receive immediate access to reliable status updates on PPE information, as well as real-time data about equipment quality, could transform how PPE is managed, ensuring that only compliant and safe equipment is used. This is particularly relevant for Romanian agriculture, where the integrity and quality of PPE are directly related to safety within the work environment and the efficiency of processes.

However, expert discussions also revealed important barriers to the implementation of blockchain technology in Romanian agriculture (Figure 2). More than half (55%) of respondents cited high implementation costs and the lack of technological infrastructure in rural areas as the top barriers to blockchain usage. This highlights an obvious area for improvement, as many rural regions in Romania do not have the high-speed internet and cutting-edge digital infrastructure required to develop blockchain applications, which demands significant investment. Additionally, 50% of the respondents identified a lack of education and training to be a major obstacle. This indicates that farmers and other stakeholders may remain on the sidelines when it comes to utilizing and deploying a new technology such as blockchain without more clarity on what it does and how it can be applied. Moreover, since most farmers rely on traditional practices, it is difficult to implement blockchain in Romanian agriculture because they might be reluctant to adopt the new skills needed or to invest in the digital tools required for blockchain. Furthermore, due to the limited number of technical personnel available to train them, exploring blockchain remains challenging. The data suggests a need for targeted education programs so that stakeholders can acquire essential knowledge about blockchain technology, reducing hesitancy and fostering an environment that supports the adoption of new technologies.

On an optimistic perspective, there is an opportunity to advocate for blockchain adoption. Three-quarters of experts (75%) endorsed the launch of pilot projects to showcase the advantages of blockchain technology in practice. This strong endorsement reflects a readiness among experts to innovate with new technologies, try them out in controlled environments, and assess blockchain's benefits while addressing any

practical challenges. Pilot projects are considered essential for scaling up: they are seen as demonstrations of blockchain's benefits, such as enhanced traceability and transparency, turning hypothetical obstacles into real-world experiences. Such projects would foster confidence among farmers and other stakeholders by proving blockchain's practicality, potentially leading to quicker acceptance and wider adoption.

The answers related to opinions on blockchain technology in Romanian agriculture are quite balanced (see Figure 2). Interest in leveraging blockchain is significant, but some key impediments continue to challenge executives. The advantages, such as enhanced traceability, increased transparency, and greater trust in the agricultural supply chain, are evident, yet financial and educational barriers associated with the technology remain substantial, experts say. There are no easy answers to whether or not to adopt blockchain in Romanian agriculture, judging by the mixed responses of those polled. People are excited about innovation; there is so much innovation that can help to address some of our world's biggest challenges, but we are still missing practical strategies to implement it and make it current and relevant to people's everyday life.

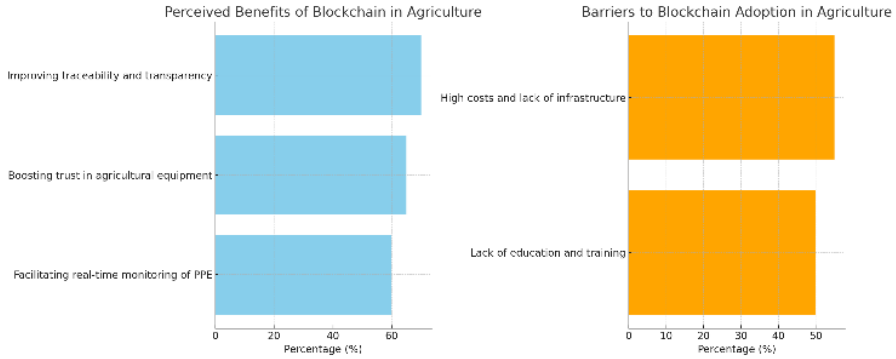

Fig. 2 - Expert perceptions on the benefits of blockchain in agriculture and the barriers to its adoption

Blockchain holds significant promise for strengthening PPE management in agriculture, offering improvements in both efficiency and sustainability. However, several considerations must be addressed to assess its practicality. Implementing this technology requires substantial investment, as well as enhancements in digital infrastructure. Additionally, increasing digital literacy among farmers and establishing a clear legislative framework should be prioritized. Without tackling these challenges, blockchain adoption in Romanian agriculture will likely remain limited, preventing the sector from fully realizing the technology's potential.

The analysis of blockchain's role in Romanian agriculture highlights benefits, challenges, and opportunities. Findings and expert insights suggest that blockchain can improve transparency, efficiency, and safety in agricultural practices, especially in PPE management. However, significant barriers could limit widespread adoption. Literature and expert input both emphasize blockchain's practical advantages, particularly for PPE traceability. Its secure, unchangeable nature enables tracking PPE across its lifecycle, from production to recycling, reducing risks of counterfeit or faulty equipment and helping to maintain safety standards. International examples from the Netherlands, the USA, and Australia show blockchain's effectiveness in PPE monitoring, enhancing transparency, consumer trust, and quality compliance, such as in PPE management on Dutch organic farms.

Achieving a balance is essential to fully unlock blockchain's potential in agriculture. This requires focused investment in infrastructure, education, and pilot projects. As shown in Figure 2, an integrated approach, guided by expert recommendations, could foster blockchain adoption in Romania. Addressing both the benefits and barriers allows Romania to leverage blockchain's capabilities in agriculture effectively. Figure 3 offers a comparison of the benefits and challenges, synthesizing scientific research and expert insights to identify factors that could either drive or hinder adoption. While the literature emphasizes the need for legislative support and political commitment, experts advocate for pilot projects and public-private partnerships as practical ways to demonstrate blockchain's value. By tackling issues such as high costs, limited infrastructure, and inadequate incentives, they propose solutions tailored to the unique needs of Romania's agricultural sector.

This research explores three possible paths for blockchain in Romanian agriculture. In an optimistic scenario, strong public-private collaboration drives adoption. In a moderate scenario, the private sector leads with limited government support. In a pessimistic scenario, blockchain adoption relies entirely on private investment, without public involvement. These scenarios create a clear framework for understanding potential directions and challenges for using blockchain, especially in PPE management.

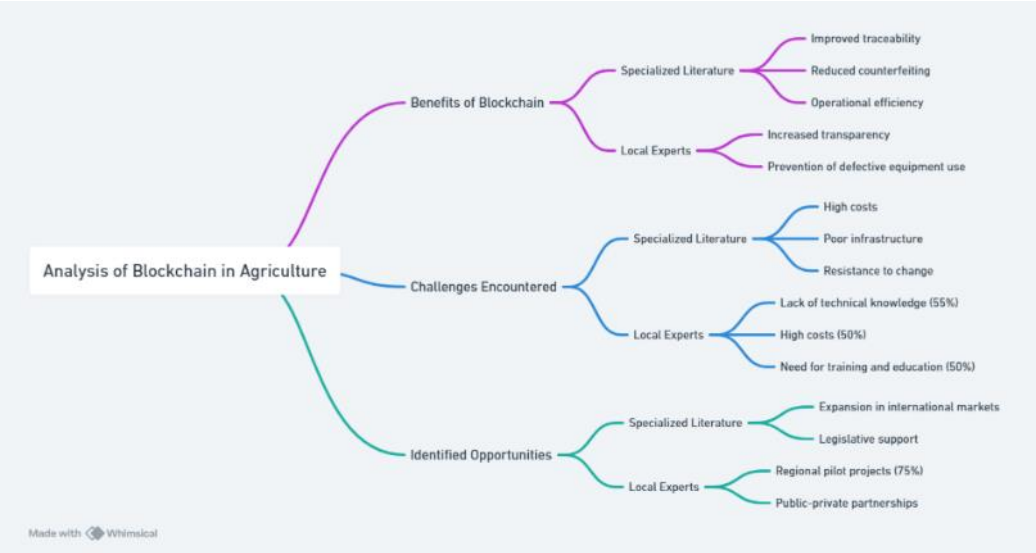

Fig. 3 - Comparison of the benefits and challenges of blockchain in Romanian agriculture

In the optimistic scenario, blockchain adoption moves advances through a strong partnership between the public and private sectors, making implementation faster and efficient. The government actively supports this process with financial support, grants, subsidies, and tax breaks, helping to reduce costs for farmers and PPE producers and promoting early adoption. This collaboration also establishes a national blockchain platform, co-managed with tech companies contributing expertise and innovation. The platform is designed to enable efficient, real-time monitoring of PPE across the supply chain by using blockchain's secure, decentralized ledger. The initial rollout includes pilot projects in regions with solid agricultural infrastructure, such as areas with established digital networks and cooperative farms. These projects serve as testing grounds to showcase the platform's ability to improve traceability and enhance operational efficiency. Within approximately two years, the blockchain platform could become operational at the national level, offering clear advantages such as enhanced transparency and traceability in PPE, which would ultimately improve safety standards and foster greater trust among farmers and consumers. This forms a self-reinforcing cycle, where initial success attracts further investment and broader adoption across the sector. Alignment between the private sector and favorable public policies, such as streamlining policies, reduced bureaucracy, and establishing lasting incentives, supports sustained growth and blockchain adoption. This creates a positive feedback loop, with the public and private sectors progressing from initial effort to steady collaboration, proving resilient and scalable in response to evolving market demands.

In the moderate scenario, blockchain implementation is led by private sector initiatives, with limited but strategic public sector support. Technology companies specializing in blockchain, PPE manufacturers, and large agricultural cooperatives collaborate to develop an independent blockchain platform suited to the unique needs and challenges of Romanian agriculture. While the public sector provides less financial backing, it plays a key supporting role by promoting partnerships, encouraging collaboration among major stakeholders, and reducing administrative and regulatory obstacles that could hinder adoption. This scenario allows for a phased and controlled approach to implementation. Initial efforts focus on high-value crops or regions with strong private sector interest, giving stakeholders a chance to test blockchain technology across different agricultural settings. These trials help identify practical challenges, such as technical issues, user acceptance, and integration with existing systems, while strategies are gradually adjusted based on real-world feedback. Although this approach moves slower than the optimistic scenario, it still delivers moderate gains in PPE traceability, transparency, and operational efficiency over time. The private sector gains from flexibility to innovate and adapt, while the public sector's limited but focused involvement provides a necessary regulatory framework and support for scaling successful models. There are risks associated with the moderate scenario. In the absence of public funding or a proper policy framework, widespread adoption might not be feasible, particularly in developing areas, or for smaller farmers who might lack the means to invest in innovative technologies. Implementation may take longer or be less rewarding since private actors will tend to pursue only those projects based on their economic and strategic profitability. In this scenario, there is a need for trust between and collaboration among private stakeholders, with the public sector focusing on creating an enabling environment for innovation and adoption of technology.

In the pessimistic scenario, blockchain adoption depends only on private investment, without any support from the public sector. This means start-ups, tech companies, and agricultural cooperatives bear on all the financial risk. They face tough challenges such as high costs, limited digital infrastructure, and the absence of legislation that might encourage new technology in agriculture. Without public grants, subsidies, or tax breaks to help with initial expenses, small and mid-sized businesses or individual farmers may find it hard to join in. Many farmers, accustomed to traditional practices, could be hesitant to adopt a complex technology like blockchain. This hesitation is made worse by the lack of training or educational programs that might help them understand blockchain's practical uses and benefits. As a result, blockchain use stays limited, seen only in a few pilot projects or small-scale initiatives. Overall, its impact on PPE management, traceability, and efficiency in agriculture remains minor, and the broader potential of blockchain technology goes mostly untapped. In this scenario, without support from the public sector, it's unlikely that blockchain adoption will expand widely. The agricultural sector risks missing out on digital advances that could improve efficiency and results. Without a clear regulatory framework, private companies also face legal uncertainties, which may discourage investment and limit the testing of blockchain.

A comparison of these three scenarios shows that a balanced approach, where public and private sectors share risks and responsibilities, offers the best path for adopting blockchain in agriculture. Public investments play a key role in building digital infrastructure, establishing clear regulations, and making technology accessible to farmers. Private investments add innovation, agility, and quick responses to market needs, supporting adaptation and scalability.

Successful implementation of blockchain requires collaboration among the public sector, private companies, technology providers, and the farming community. This collaborative model could improve operational efficiency, boost traceability, and enhance the safety of protective equipment in agriculture. It would also address barriers like high costs, limited infrastructure, and resistance to new technology by pooling resources and coordinating efforts.

These scenarios show different pathways for implementing blockchain in Romanian agriculture and underscore the need for a supportive environment with public investment in education, training, and infrastructure. The findings indicate that while blockchain has strong potential to improve PPE management in agriculture, its success will depend on coordinated efforts from both the public and private sectors. This collaborative effort may include additional investments in training programs to boost digital literacy among farmers, reduce resistance to new technologies, and establish a legislative framework that encourages innovation and supports blockchain adoption. The future of blockchain in Romanian agriculture depends on the commitment partnership of both public and private stakeholders willing to invest and collaborate to overcome existing challenges. A combined approach, drawing on the strengths of each sector, is essential for realizing blockchain's potential and building a more efficient, transparent, and sustainable agricultural system.

Figure 4 maps out the decision-making process, highlighting on the key steps and points essential for implementation across the different scenarios. The success of blockchain adoption depends on several factors: the readiness of digital infrastructure, available financial resources, stakeholder commitment, and a supportive regulatory framework. A balanced strategy, combining public support with private innovation, can create a sustainable model for blockchain adoption, improving traceability, efficiency, and safety in PPE management in agriculture.

The flowchart for implementing blockchain in Romania's agricultural sector begins by identifying needs for better traceability and sustainability in PPE management. Initially, it reviews specific areas where blockchain could improve processes, from production to recycling. Following this, an evaluation of costs and infrastructure is conducted, considering available funding, existing technology, and the readiness of farmers and stakeholders to adopt this approach. If resources are determined to be adequate, the plan advances to execution with support from public institutions and private companies. In the absence of sufficient resources, the diagram suggests seeking supplementary funding sources, such as grants or subsidies.

A key decision point assesses whether costs and infrastructure meet project needs. If these conditions are met, the process advances to a pilot phase to test blockchain in a controlled setting. This stage allows for adjustments to technology and strategy, based on outcomes across different regions. Positive results from the pilot phase lead to a recommendation for nationwide implementation, potentially positioning Romania as a leader in agricultural technology. If results don't meet expectations, the strategy may require adjustments, which could include technology improvements, new partnerships, or additional funding, with two final options: broader adoption if successful, or a revised approach if necessary.

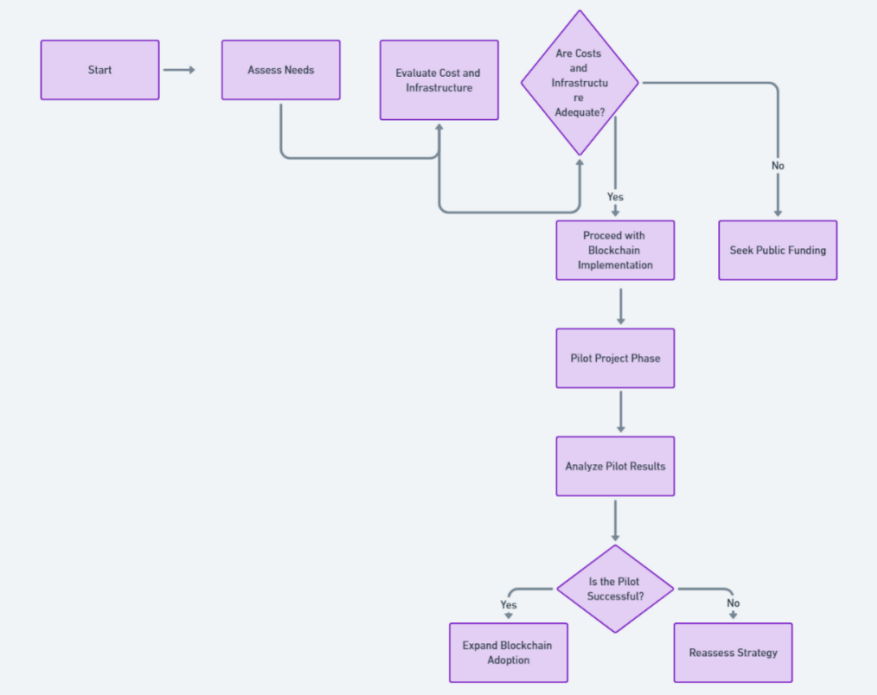

Fig. 4 - Flowchart for decision-making in implementing blockchain for agriculture PPE management

The flowchart presents a systematic method for integrating blockchain technology into the agricultural sector, emphasizing the necessity of collaboration between public and private entities to overcome challenges and amplify benefits. It provides guidance for decision-makers and stakeholders to identify essential actions and decisions necessary for effective and sustainable blockchain adoption. Both the expert opinion chart (Figure 2) and the flowchart (Figure 4) indicate that successful blockchain implementation relies on a combination of resources, government support, and local stakeholder engagement. The proposed scenarios offer a foundation for creating strategies tailored to the specific needs of Romanian agriculture.

Recent research underscore blockchain's transformative potential in agricultural supply chains, while also pointing out the challenges of its implementation. A report from the *Food and Agriculture Organization (FAO)* suggests that blockchain could significantly boost transparency, traceability, and operational efficiency, improve market access for smallholder farmers, reduce intermediary involvement, and promote fair pricing. However, the report also notes several barriers, including unclear regulations, the absence of universal standards, and insufficient infrastructure in rural areas *(FAO, 2024).* Additionally, another research suggests that integrating blockchain with Internet of Things (IoT) devices could improve the agricultural data management, but it also raises concerns about the high costs of implementation, legal uncertainties related to smart contracts, and connectivity limitations *(AGDAILY, 2024).* A systematic review of blockchain in the agri-food supply chain indicates that, whereas the technology can improve food safety, its adoption is limited by the need for significant investments, technical skills, and supportive policies *(Management Review Quarterly, 2024).* This aligns with the observations of *Walaszczyk et al. (2022)*, who note that evolving consumer expectations are likely to boost demand for better food traceability and secure, tamper-proof systems. A robust traceability process provides consumers with comprehensive "farm to fork" information, enhancing food safety oversight and underscoring the importance of such innovations within the agri-food sector.

This study encounters several limitations. Information derived from discussions with regional experts and literature reviews may introduce bias, as expert opinions are often shaped by personal experiences, which could limit the broader applicability of the results. Since the research is focused on agriculture in Romania, findings may not apply to regions with different technological, economic, or regulatory contexts. Additionally, the proposed implementation scenarios rely on projections and assumptions regarding costs, infrastructure, and political support, which may not fully capture actual conditions or account for variables such as economic changes, policy shifts, or rapid technological advances that could impact blockchain adoption. Additionally, the proposed implementation scenarios are based on projections and assumptions about costs, infrastructure, and political backing, which might not accurately represent actual conditions or take into account factors such as economic fluctuations, policy changes, or rapid technological advancements that could influence the adoption of blockchain technology.

Future research should involve empirical studies that collect quantitative and qualitative data from a diverse range of stakeholders, farmers, distributors, and regulatory bodies, to better understand blockchain's potential in agriculture. Comparative case studies across different regions could highlight effective practices and successful strategies. Additionally, research should assess the economic impact of blockchain on farmers' incomes, market transparency, and operational efficiency. Developing regulatory frameworks and supportive policies for blockchain implementation, along with exploring international collaboration for a favorable legislative environment, are essential areas for further investigation.

CONCLUSIONS

Blockchain technology can enhance the traceability and sustainability of PPE in Romanian agriculture. By enabling secure and transparent monitoring throughout the PPE lifecycle, it ensures compliance with safety standards and reduces counterfeit risks. These features contribute to safer working conditions and support sustainable agricultural practices.

The adoption of blockchain faces significant barriers, including high costs, inadequate digital infrastructure in rural areas, and low digital literacy among farmers. Strategic investments in infrastructure and customized training programs are necessary to address these challenges and enable wider adoption.

Collaborations between public institutions and private stakeholders are critical for providing funding, developing infrastructure, and offering training. Such partnerships can demonstrate blockchain’s benefits, build trust among users, and create a solid foundation for large-scale implementation. Pilot projects serve as valuable testing grounds, allowing stakeholders to identify challenges, refine strategies, and showcase blockchain’s value before scaling up. Clear and supportive legislation is essential to encourage investment and reduce regulatory uncertainty. A well-defined legal framework will enable seamless integration of blockchain into agricultural practices, fostering trust and confidence among stakeholders. A balanced approach, combining public and private efforts, is key to overcoming existing barriers.

By addressing these issues and leveraging partnerships, blockchain can transform Romanian agriculture into a safer, more efficient, and sustainable sector.

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