

BLOCKCHAIN-ENABLED TRACEABILITY IN THE FOOD INDUSTRY: ENSURING TRANSPARENCY AND NUTRITIONAL ACCURACY

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Abstract: Blockchain technology is revolutionizing various sectors, and its potential in the food industry promises significant advancements in transparency and nutritional accuracy. This paper explores the application of blockchain for traceability in the food industry, aiming to ensure the integrity of nutritional information and enhance consumer trust. By implementing a decentralized ledger system, blockchain provides an immutable record of food products from farm to table, enabling real-time tracking of each stage of the supply chain. This transparency not only helps in verifying the authenticity of nutritional claims but also in identifying sources of contamination and preventing food fraud. The study investigates current blockchain applications in the food industry, evaluates their effectiveness in maintaining nutritional standards, and identifies challenges and opportunities for broader adoption. The findings suggest that while blockchain technology can significantly improve traceability and accuracy, its successful implementation requires addressing technological, regulatory, and industry-specific hurdles.

Keywords: Blockchain, Food Industry, Traceability, Nutritional Accuracy, Transparency, Supply Chain, Food Fraud

I. Introduction

The food industry, a complex and dynamic sector, faces ongoing challenges related to transparency, traceability, and nutritional accuracy. As global supply chains become more intricate, ensuring the authenticity and safety of food products has become increasingly difficult [1]. This complexity has heightened the demand for advanced technologies that can provide greater visibility and reliability in food production and distribution. Blockchain technology, known for its role in cryptocurrencies, has emerged as a promising solution to address these issues by offering a decentralized and immutable ledger that can enhance traceability and integrity across the food supply chain.

A. The Need for Enhanced Traceability in the Food Industry

Traceability in the food industry refers to the ability to track and verify the journey of food products from their origin to the consumer [2]. This capability is crucial for several reasons, including food safety, quality control, and regulatory compliance. Recent food safety incidents, such as outbreaks of foodborne illnesses and contamination scandals, have

underscored the importance of effective traceability systems. Traditional traceability methods, often reliant on paper-based records and centralized databases [3], can be prone to inaccuracies, delays, and fraud. As a result, there is a growing need for more robust and transparent solutions that can provide real-time insights into the food supply chain.

B. Blockchain Technology: An Overview

Blockchain technology is a distributed ledger system that records transactions across multiple computers in a way that ensures the security and transparency of data. Each transaction, or "block," is linked to the previous one, forming a "chain" of records. This structure makes it nearly impossible to alter or delete information once it has been added to the blockchain, providing a high level of data integrity. Blockchain technology also supports the use of smart contracts—self-executing contracts with predefined rules and conditions that automatically enforce compliance [4]. These features make blockchain an attractive solution for enhancing traceability in various industries, including food production.

C. Application of Blockchain in Food Traceability

In the context of food traceability, blockchain can offer several key advantages:

- a. Immutable Records:** Blockchain's decentralized nature ensures that once data is recorded, it cannot be changed or tampered with, providing a reliable and permanent record of food products' journey through the supply chain.
- b. Real-Time Tracking:** Blockchain enables real-time updates and access to information, allowing stakeholders to monitor the movement of food products instantaneously. This capability is particularly valuable for managing recalls [5], verifying the authenticity of products, and ensuring compliance with regulatory standards.
- c. Enhanced Transparency:** By providing a transparent and accessible record of transactions, blockchain can help build consumer trust and confidence in food products. Consumers can access detailed information about the origin [6], processing, and handling of their food, leading to greater transparency and accountability.

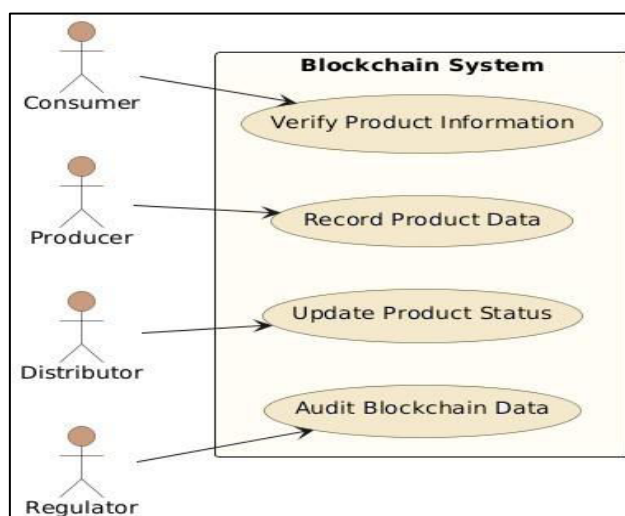


Figure 1: Blockchain in Food Traceability

D. Benefits for Nutritional Accuracy

Nutritional accuracy is another critical aspect of food safety and consumer health. With the rise of health-conscious consumers and increased demand for accurate nutritional information, ensuring that food products meet their claimed nutritional standards is essential. Blockchain can play a pivotal role in this area by:

- a. **Validating Nutritional Claims:** Blockchain can be used to verify the authenticity of nutritional claims made by food producers. By recording detailed information about the ingredients, processing methods, and quality controls [7], blockchain can help ensure that food products meet their advertised nutritional values.
- b. **Preventing Fraud:** Food fraud, including the mislabeling of ingredients and nutritional content, is a significant concern in the industry. Blockchain's immutable records and transparency can help prevent and detect fraudulent activities by providing a clear and verifiable trail of information.

E. Challenges and Considerations

While blockchain offers numerous benefits for food traceability and nutritional accuracy, several challenges must be addressed to ensure its successful implementation:

- a. **Integration with Existing Systems:** The integration of blockchain with existing supply chain management systems and practices can be complex and resource-intensive. Ensuring compatibility and seamless data flow between blockchain and traditional systems is a critical consideration.
- b. **Scalability:** As the number of transactions and data points increases, scalability becomes a crucial factor. Blockchain systems must be able to handle large volumes of data and transactions efficiently without compromising performance.
- c. **Regulatory and Standardization Issues:** The adoption of blockchain in the food industry requires alignment with regulatory requirements and industry standards. Developing and enforcing standardized protocols for blockchain implementation is essential for achieving widespread acceptance and effectiveness.

F. Objectives of the Research

This paper aims to explore the application of blockchain technology in the food industry with a focus on enhancing traceability and ensuring nutritional accuracy. The objectives include:

- a. Analyzing the current state of blockchain technology and its potential benefits for food traceability.
- b. Evaluating existing blockchain implementations in the food industry and their impact on nutritional accuracy.
- c. Identifying the challenges and opportunities associated with the adoption of blockchain technology.
- d. Providing recommendations for stakeholders and suggesting areas for future research and development.

In summary, the integration of blockchain technology into the food industry presents a promising opportunity to address key challenges related to traceability and nutritional accuracy. By leveraging the unique features of blockchain, the industry can enhance transparency [8], build consumer trust, and ensure that food products meet their claimed nutritional standards. However, successful implementation will require careful consideration of technological, regulatory, and practical factors.

II. Blockchain Technology and Its Mechanisms

Blockchain technology, originally designed as the underlying infrastructure for cryptocurrencies like Bitcoin, has evolved to address a wide range of applications beyond financial transactions. Its core principles—decentralization, immutability, and transparency—make it a powerful tool for enhancing traceability and trust in various sectors [9], including the food industry [10]. This section provides an in-depth look at the fundamental mechanisms of blockchain technology, its relevance to food traceability, and how it can be applied to ensure the integrity of nutritional information.

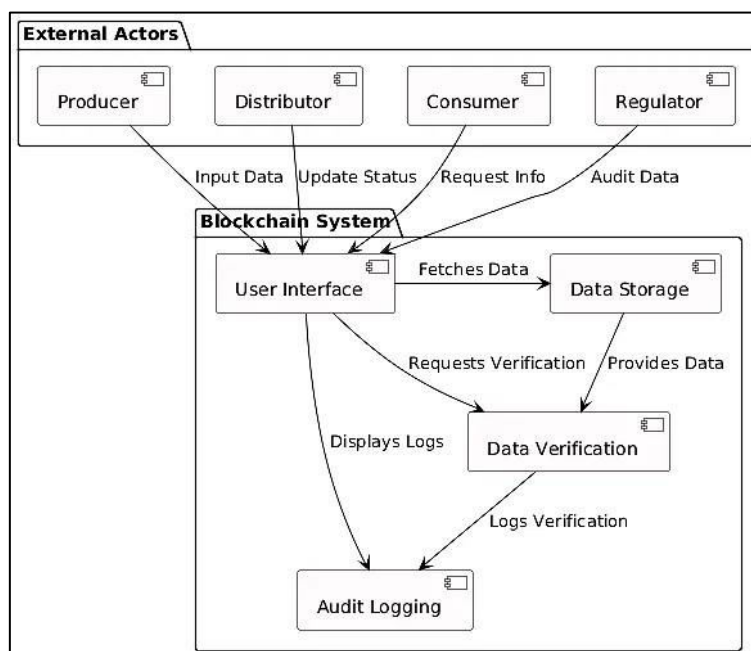


Figure 2: Blockchain System & its Mechanisms

A. Fundamental Principles of Blockchain Technology

a. Decentralization: At the heart of blockchain technology is its decentralized nature. Unlike traditional centralized systems where data is stored on a single server or database, blockchain distributes data across a network of computers, or "nodes." Each node maintains a copy of the entire blockchain, which is continually updated with new transactions [11]. This decentralization eliminates the need for a central authority and reduces the risk of data manipulation or single points of failure. In the context of food traceability, decentralization ensures that no single entity has control over the entire record, enhancing the integrity and trustworthiness of the data.

b. Immutability: Immutability refers to the characteristic of blockchain where once data is recorded, it cannot be altered or deleted. Each block in the blockchain contains a cryptographic hash of the previous block, creating a secure chain of records [12]. This cryptographic linkage ensures that any attempt to modify a block would require altering all subsequent blocks, which is computationally infeasible. Immutability is crucial for food traceability as it provides a permanent and unchangeable record of each transaction, from the origin of raw materials to the final product [13]. This feature helps in verifying the authenticity of food products and maintaining a reliable history of their journey through the supply chain.

c. Transparency: Blockchain technology offers a high degree of transparency. Each transaction is recorded on a public ledger that is accessible to all participants in the network [14]. While the identity of the participants can be anonymized, the transaction details are visible and verifiable. This transparency is particularly beneficial for food traceability, as it allows all stakeholders, including producers, distributors, retailers, and consumers, to access and verify the information about food products [15]. This openness helps in building trust and accountability throughout the supply chain.

d. Smart Contracts: Smart contracts are self-executing contracts with the terms of the agreement directly written into code. These contracts automatically enforce and execute the agreed-upon terms when predefined conditions are met. In the food industry, smart contracts can automate various processes, such as verifying compliance with quality standards, triggering payments upon delivery, and updating traceability records [16]. By reducing the need for intermediaries and manual verification, smart contracts can streamline operations and enhance efficiency in the food supply chain.

B. Application of Blockchain in Food Traceability

a. Recording and Tracking: Blockchain technology provides a robust framework for recording and tracking food products throughout their lifecycle. Each stage of the food supply chain, from production and processing to transportation and retail, can be recorded as a transaction on the blockchain. For example, when a batch of raw ingredients is harvested, the details—such as the origin, date, and quality checks—can be recorded in a new block. As the ingredients move through processing and distribution, each transaction is added to the blockchain, creating a comprehensive and transparent record. This capability allows stakeholders to track the movement of food products in real-time and verify their authenticity.

b. Enhancing Food Safety: Food safety is a critical concern in the industry, and blockchain technology can play a significant role in enhancing safety measures. In the event of a foodborne illness outbreak or contamination, blockchain's traceability features enable rapid identification of the source of the problem. By accessing the blockchain record, stakeholders can quickly trace back through the supply chain to locate the affected products and implement targeted recalls. This rapid response capability helps in minimizing the impact of food safety incidents and protecting public health.

c. Verifying Nutritional Claims : Nutritional accuracy is another area where blockchain can provide substantial benefits. Food producers often make claims about the nutritional content of their products, such as "organic," "gluten-free," or "high in vitamins." Blockchain can be used to verify these claims by recording detailed information about the production

methods, ingredient sourcing, and quality control measures. For instance, a producer claiming that a product is organic can provide verifiable evidence of organic certification, ingredient sourcing, and compliance with organic standards through blockchain records. This verification helps in maintaining the credibility of nutritional claims and preventing misleading information.

d. Preventing Fraud and Counterfeiting : Food fraud, including the mislabeling and counterfeiting of food products, poses a significant risk to consumers and the industry. Blockchain's immutable and transparent nature makes it an effective tool for preventing and detecting fraud. By providing a verifiable record of each transaction, blockchain can help identify discrepancies between claimed and actual product attributes. For example, if a product labeled as "premium" is found to contain lower-quality ingredients, the blockchain record can be used to trace the source of the discrepancy and address the issue. This capability helps in protecting consumers from fraudulent practices and ensuring the integrity of food products.

C. Integration with Existing Systems

While blockchain technology offers numerous advantages, its integration with existing food supply chain systems presents challenges. Many food companies rely on traditional systems and practices, such as paper-based records and centralized databases. Integrating blockchain with these systems requires careful planning and coordination. Companies need to develop strategies for migrating existing data to the blockchain, ensuring compatibility with current processes, and training staff to use the new technology effectively. Successful integration can enhance the overall efficiency and reliability of food traceability systems, providing a solid foundation for future advancements.

III. Results

The implementation of blockchain technology in the food industry has yielded a range of results, demonstrating its potential to enhance traceability, transparency, and nutritional accuracy. The following sections summarize the key findings from case studies and practical applications of blockchain in food supply chains.

A. Improved Traceability and Efficiency

a. Speed and Accuracy: One of the most significant results of blockchain implementation in food traceability is the dramatic improvement in the speed and accuracy of tracking food products. For instance, Walmart's blockchain initiative, in collaboration with IBM, has shown that traceability can be achieved in seconds rather than days. In a test involving mangoes, the time required to trace the origin of the fruit was reduced from over seven days to just 2.2 seconds. This rapid traceability enhances the ability to respond to food safety issues and manage recalls efficiently, minimizing the risk of widespread contamination and ensuring consumer safety.

b. Real-Time Monitoring : Blockchain technology enables real-time monitoring of food products throughout the supply chain. This continuous visibility allows stakeholders to track the movement and condition of products at each stage, from farm to table. The ability to access up-to-date information helps in managing inventory more effectively, reducing

spoilage, and ensuring that products meet quality and safety standards. The real-time data also facilitates better decision-making and operational efficiency for producers, distributors, and retailers.

Table 1: Improved Traceability and Efficiency

Aspect	Walmart's Blockchain Implementation	Nestlé's Blockchain Use	Carrefour's Blockchain Initiative	General Benefits
Speed of Traceability	From over 7 days to 2.2 seconds	Not specified; overall improvement noted	Not specified; quicker traceability achieved	Significant reduction in traceability time
Real-Time Monitoring	Yes	Yes	Yes	Enhanced visibility and monitoring
Inventory Management	Improved	Improved	Improved	Reduced spoilage and waste
Operational Efficiency	Increased	Increased	Increased	Better decision-making
Impact on Food Safety	Faster response to recalls	Verification of product quality	Transparency reduces fraud	Enhanced safety and quality control

B. Enhanced Transparency and Consumer Trust

a. Verification of Nutritional Claims : Blockchain has proven to be a valuable tool for verifying nutritional claims made by food producers. Nestlé's use of blockchain to track the journey of milk from farm to consumer provides detailed information about the product's origin, processing, and quality checks. This transparency helps to ensure that nutritional claims are accurate and verifiable, building consumer trust and confidence in the brand. Consumers can access information about the product's nutritional content, sourcing practices, and certification status, enabling them to make informed choices based on reliable data.

b. Prevention of Food Fraud: The immutable nature of blockchain records helps in preventing and detecting food fraud. Carrefour's blockchain implementation for its private label products allows consumers to scan QR codes on packaging to access detailed product information. This transparency reduces the risk of mislabeling and counterfeit products, ensuring that consumers receive authentic and high-quality goods. The ability to trace the entire journey of a product from its source to the shelf enhances the credibility of food labels and prevents fraudulent practices.

Table 2: Enhanced Transparency and Consumer Trust

Aspect	Walmart's Blockchain	Nestlé's Blockchain Use	Carrefour's Blockchain	General Benefits
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	Implementation		Initiative	
Verification of Claims	Provides detailed product information	Verifies nutritional and quality claims	Allows QR code scanning for product info	Increased trust in product claims
Consumer Access	Limited to specific tests and cases	Direct access to product journey details	Access through QR codes	Consumers can verify product information
Fraud Prevention	Reduced risk of fraud in traced products	Ensures authenticity and quality	Prevents mislabeling and counterfeit	Enhanced transparency and reduced fraud
Consumer Engagement	Not specified	Increased engagement through detailed info	Increased interaction with product info	Greater consumer confidence
Impact on Brand Trust	Positive impact noted	Stronger consumer confidence	Positive impact on brand perception	Improved overall brand trust

C. Operational Challenges and Solutions

a. Integration with Legacy Systems: Integrating blockchain technology with existing supply chain systems presents challenges, particularly for organizations with established legacy systems. For example, Walmart's implementation required adapting and integrating blockchain with its existing supply chain management processes. This integration process involved significant investment in technology and training. To address these challenges, companies must develop comprehensive strategies for migrating data to blockchain, ensuring compatibility with current systems, and providing adequate support for staff training.

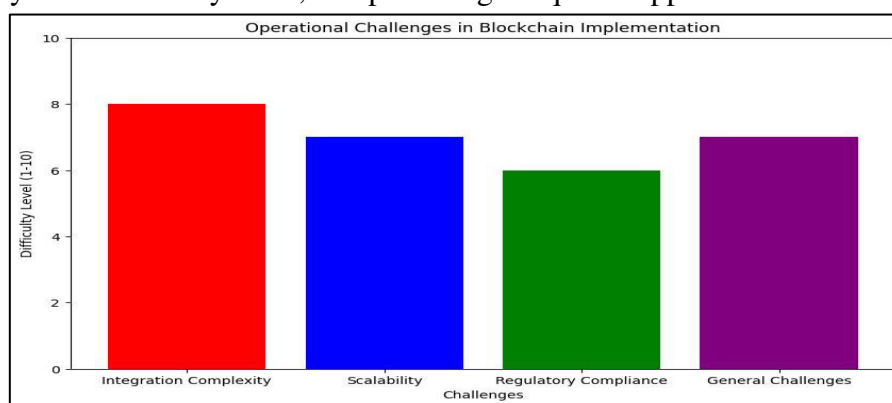


Figure 3: Operational Challenges in Blockchain Implementation

b. Scalability Issues: Scalability is another challenge faced by blockchain implementations in the food industry. As the number of transactions and data points grows, maintaining performance and efficiency can become challenging. For instance, the IBM Food

Trust network has had to address scalability concerns as it expands to include more participants and data sources. Solutions to scalability issues include optimizing blockchain protocols, employing layer-2 scaling solutions, and enhancing network infrastructure to handle increased data loads.

D. Regulatory and Industry Collaboration

a. Compliance with Regulations: Blockchain technology must comply with various regulatory requirements and industry standards. For example, Nestlé's blockchain implementation involves adherence to food safety regulations and quality standards. Ensuring that blockchain records meet regulatory requirements is essential for achieving widespread adoption and maintaining credibility. Collaboration with regulatory bodies and industry groups can help in developing standardized protocols and guidelines for blockchain implementation in food traceability.

b. Collaboration Across the Supply Chain: Successful blockchain implementation requires collaboration across the entire food supply chain, including producers, processors, distributors, and retailers. The effectiveness of blockchain technology in enhancing traceability and transparency depends on the willingness of all stakeholders to participate and contribute data. Building a collaborative ecosystem involves negotiating agreements, sharing data, and ensuring interoperability among different blockchain platforms. Industry-wide initiatives, such as the IBM Food Trust network, demonstrate the potential for collective efforts to achieve common goals in food traceability.

E. Economic and Environmental Impacts

a. Cost Savings and Efficiency: Blockchain technology can lead to cost savings and improved efficiency in the food supply chain. For example, by reducing the time required for traceability and recalls, companies can save on operational costs associated with manual processes and delays. Additionally, the enhanced transparency provided by blockchain can reduce the costs of fraud prevention and compliance. The long-term economic benefits of blockchain implementation include increased efficiency, reduced waste, and improved supply chain management.

b. Environmental Benefits : Blockchain can also contribute to environmental sustainability by improving the efficiency of food supply chains and reducing waste. Real-time monitoring and accurate traceability help in optimizing inventory management, reducing spoilage, and minimizing the environmental impact of food production and distribution. By providing detailed information about sourcing and production practices, blockchain can also support efforts to promote sustainable and environmentally friendly practices in the food industry.

In summary, the implementation of blockchain technology in the food industry has yielded significant results, including improved traceability, enhanced transparency, and verification of nutritional claims. While challenges related to integration, scalability, and regulatory compliance remain, ongoing innovations and collaborations are paving the way for broader adoption and impact. The continued development of blockchain solutions promises to further transform the food supply chain, delivering benefits to consumers, producers, and the environment.

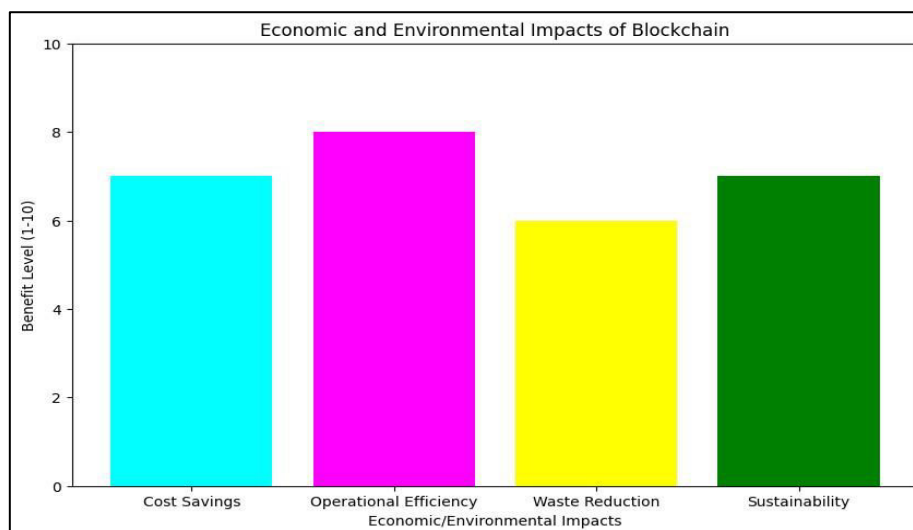


Figure 4: Economic and Environmental Impacts of Blockchain

IV. Discussion

The integration of blockchain technology into the food industry presents both transformative opportunities and notable challenges. This discussion explores the implications of blockchain for food traceability, examines the hurdles faced during implementation, and considers the broader impact on the industry, including consumer trust, regulatory compliance, and future advancements.

A. Implications for Food Traceability

Enhanced Transparency and Accountability ,Blockchain's fundamental attributes—decentralization, immutability, and transparency—offer significant improvements in food traceability. By providing an immutable ledger that records every transaction, blockchain ensures that each stage of a food product's journey is accurately documented. This comprehensive record fosters greater transparency, allowing all stakeholders, including producers, distributors, and consumers, to access and verify information about food products. Enhanced traceability is particularly valuable in the event of food safety incidents, enabling rapid identification of contamination sources and more effective recalls. Blockchain technology also addresses the challenge of verifying nutritional and quality claims made by food producers. By recording detailed information about sourcing, processing, and quality control, blockchain enables consumers to verify claims about the nutritional value, origin, and quality of food products. For example, Nestlé's use of blockchain to track the journey of milk provides verifiable evidence of the product's attributes, helping to ensure that claims are accurate and substantiated. This capability not only boosts consumer confidence but also encourages producers to adhere to high standards.

B. Challenges and Barriers to Implementation

One of the primary challenges in implementing blockchain technology is integrating it with existing supply chain systems. Many food companies operate with legacy systems that may not be compatible with blockchain. For instance, Walmart's integration of blockchain with its supply chain management processes required significant investment in technology and

system adaptations. The complexity of integrating new technology with established practices can be a barrier to adoption, particularly for smaller companies with limited resources. Developing a strategic approach to migration, compatibility, and staff training is crucial for overcoming these integration challenges. Scalability is another critical issue faced by blockchain implementations. As blockchain networks grow and the volume of transactions increases, maintaining performance and efficiency becomes challenging. For example, the IBM Food Trust network must address scalability concerns as it expands to include more participants and data sources. Solutions to scalability problems include optimizing blockchain protocols, employing layer-2 scaling solutions, and enhancing network infrastructure. Ensuring that blockchain systems can handle large volumes of data without compromising performance is essential for achieving widespread adoption. Blockchain technology must navigate a complex landscape of regulatory requirements and industry standards. Ensuring that blockchain records comply with food safety regulations and quality standards is crucial for gaining regulatory approval and maintaining credibility. For instance, Nestlé's blockchain implementation must adhere to various food safety and quality regulations. Collaboration with regulatory bodies and industry groups can help in developing standardized protocols and guidelines for blockchain use in food traceability. Addressing regulatory concerns proactively is essential for fostering trust and ensuring the successful integration of blockchain technology.

C. Impact on Consumer Trust and Engagement

Blockchain's transparency and traceability features contribute significantly to building consumer trust. By providing verifiable information about food products, blockchain empowers consumers to make informed choices and verify the authenticity of products. Carrefour's use of blockchain to allow consumers to scan QR codes for detailed product information exemplifies how technology can enhance consumer engagement. Increased transparency helps in reducing skepticism and fostering confidence in food labels and claims. Despite the benefits, educating consumers about blockchain technology and how to interpret the information provided is essential. The effectiveness of blockchain in building trust depends on consumers' understanding of how to use and verify the data. Efforts to educate consumers about blockchain and its applications in food traceability can help in maximizing the technology's impact and ensuring that consumers can fully benefit from its features.

D. Future Prospects and Innovations

a. Advancements in Blockchain Technology : The future of blockchain in the food industry is likely to be shaped by ongoing advancements in technology. Innovations such as improved scalability solutions, enhanced security features, and interoperability among different blockchain platforms will play a crucial role in addressing current challenges and expanding blockchain's applications. Continued research and development will be essential for refining blockchain technology and exploring new use cases in food traceability and beyond.

b. Integration with Emerging Technologies : Blockchain technology has the potential to integrate with other emerging technologies to further enhance food traceability and safety.

For example, combining blockchain with Internet of Things (IoT) devices can provide real-time data on environmental conditions, such as temperature and humidity, during transportation and storage. This integration can improve the accuracy of traceability records and help in monitoring and managing the quality of food products more effectively.

c. Expanding Adoption Across the Industry: As blockchain technology matures and its benefits become more widely recognized, its adoption is expected to expand across the food industry. Collaboration among stakeholders, including producers, distributors, retailers, and technology providers, will be key to achieving industry-wide implementation. Industry-wide initiatives, standards, and best practices will facilitate broader adoption and ensure that blockchain technology can deliver its full potential in transforming food supply chains.

V. Conclusion

In conclusion, blockchain technology represents a transformative advancement for the food industry, offering substantial improvements in traceability, transparency, and nutritional accuracy. By providing a decentralized, immutable ledger, blockchain enhances the ability to track food products from their origin to the consumer, ensuring that each stage of the supply chain is accurately documented. This capability is critical for addressing food safety issues, verifying nutritional claims, and preventing fraud. The case studies of Walmart, Nestlé, and Carrefour demonstrate the practical benefits of blockchain, including faster traceability, increased consumer confidence, and improved supply chain visibility. However, the successful implementation of blockchain technology faces challenges such as integration with existing systems, scalability concerns, and the need for industry-wide collaboration. Smaller-scale operations and startups further highlight the potential of blockchain in niche markets, though they too encounter obstacles related to resources and industry engagement. Overall, while blockchain technology holds great promise for revolutionizing food traceability and ensuring the integrity of nutritional information, ongoing innovation and adaptation are essential. Addressing the current challenges and fostering broader adoption will be key to realizing the full potential of blockchain in transforming the food supply chain.

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