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Artificial Intelligence, Blockchain, and IoT in Modern Biomaterials and Food Supply Chain Operations

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ABSTRACT

The integration of Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT) is revolutionizing food supply chain management by enhancing efficiency, transparency, and security. AI aids in optimizing production and demand forecasting, significantly reducing costs and waste through advanced analytics. Blockchain, with its decentralized and immutable data structure, offers unparalleled transparency by recording each stage of food production and distribution, thus minimizing fraud and ensuring traceability. IoT, through the use of connected devices and sensors, provides real-time data on factors like storage conditions and transportation, enabling swift responses to potential issues. Together, these technologies mitigate supply chain vulnerabilities exposed during events like the COVID-19 pandemic and promote a smarter, more resilient food distribution system. Despite the promise of these technologies, challenges such as blockchain's energy consumption and legal complexities still need to be addressed. Ultimately, the convergence of AI, Blockchain, and IoT in the food supply chain holds the potential for creating a more efficient, secure, and sustainable industry. The convergence of AI, Blockchain, and IoT in biomaterials and food supply chains represents a significant advancement, fostering innovation and efficiency while addressing critical challenges in sustainability and safety. As these technologies continue to evolve, their impact will likely grow, revolutionizing the industry.

1. Introduction

In an era where global food supply chains face unprecedented challenges, the convergence of cutting-edge technologies such as Artificial Intelligence, Blockchain, and the Internet of Things is ushering in a transformative phase in food supply chain management. These innovations are not merely enhancing existing processes; they are redefining how food is produced, tracked, and distributed across the globe [1]. AI's capacity for advanced analytics empowers producers with precise demand forecasting and production optimization, significantly cutting costs and minimizing waste. Meanwhile, Blockchain's decentralized and immutable nature offers a robust solution for enhancing transparency and trust, ensuring that every stage of food production and distribution is traceable [3-6]. Complementing these technologies, IoT connects devices and sensors to provide real-time insights into storage conditions and transportation logistics, allowing stakeholders to respond proactively to potential disruptions. As highlighted during the COVID-19 pandemic, these technologies are essential for building a resilient and efficient food distribution system. However, despite their promise, challenges such as energy consumption and legal complexities surrounding Blockchain remain significant hurdles. This article delves into the synergistic benefits and potential obstacles of integrating AI, Blockchain, and IoT within the food supply chain, illustrating how their collective power could lead to a more sustainable and secure food industry [2]. This article investigates the synergistic integration of Artificial Intelligence, Blockchain, and the Internet of Things within biomaterials and food supply chains. Its objective is to explore how these technologies can enhance operational efficiency and sustainability while ensuring product safety and traceability. The novelty lies in presenting a comprehensive framework that highlights the interconnected roles of these technologies, offering insights into their collective impact on industry practices. This contribution aims to inform stakeholders about innovative strategies for optimizing supply chains, fostering transparency, and building consumer trust in food quality and biomaterial integrity.

2. Managing the Food Supply Chain in Business

Historically, the utilization of supply chain management was an occasional decision, yet looking ahead, this approach is destined to become an enduring imperative. In the future, SCM will predominantly navigate the equilibrium between planning and execution, with its optimal functioning contingent on speed and precision. At some point, your business will inevitably require the adoption of this strategy and corresponding software; timely implementation can confer a competitive advantage in the realm of SCM [6-11]. It equips businesses with three principal tools that facilitate their growth across distinct domains. The first domain entails the identification of potential issues, emphasizing the provision of essential information to pre-empt challenges before their manifestation [3]. Adept supply chain management identifies consistently returned items and initiates corrective measures or retrieves them before compromising customer trust and confidence. The second domain encompasses balanced and dynamic pricing, intimately linked to pricing strategies. Recognizing that not all products exhibit uniform sales and popularity throughout the year, supply chain management aids in discerning and evaluating factors influencing product prices, subsequently adjusting and harmonizing them. Nevertheless, dynamic pricing does not present uniform risks and challenges for all enterprises, diverging based on organizational specifics. The third domain revolves around market analysis, wherein SCM furnishes tools for scrutinizing sales and demand. Insights into sales forecasts, order predictions, and delivery planning contribute to meticulous planning and customer retention [4].

3. Implementing Software Solutions in Food Supply Chain Management

Supply chain management necessitates an operational framework grounded in demand, harmonizing individuals, processes, and technologies. Within this framework, products and services are delivered with noteworthy swiftness and precision. Advanced and contemporary software effectively encompasses all these functions. While organized and intelligent supply chain management has perennially been vital, it is presently regarded as imperative and a guarantor of business survival. Procurement and logistics software also furnish additional advantages, augmenting their intrinsic value. A critical consideration is the selection of suitable and recognized software capable of streamlining tasks [5]. Supply chain management is centred around responsiveness, delivery, customer experience, and satisfaction, with cost reduction playing a pivotal role. On the one hand, managerial sectors must be pertinent and aligned with consumer needs. On the other hand, resource identification, formulation of appropriate commercial laws and policies, and implementation of efficacious transportation methods are indispensable in this strategic approach. Technology is evidently progressing to enhance supply chain management, with software persistently evolving and advancing [6].

Procurement and logistics software aid businesses by fostering integration across diverse data points throughout the supply chain, ensuring a unified perspective across distinct business segments and facilitating optimal supply chain management. Inventory management, cost control, supplier management, and centralized branch oversight represent only a subset of the capabilities that the procurement and logistics software solution will afford your business. In 2019, the unforeseen waves of turmoil and disruption that unfolded in 2020 caught everyone by surprise. The global business community received a stark warning from the impact of COVID-19, shedding light on the vulnerability and outdated nature of certain supply processes. To put it differently, an ineffective and poorly coordinated supply chain has the potential to inflict severe damage on small and medium-sized businesses (SMBs). Concerns arising from issues like loss during transportation, delivery, and unexplained costs incurred to reach customers could significantly influence customer preferences towards rival offerings. A myriad of emerging and novel technologies is reshaping the landscape of digital procurement. Artificial intelligence and machinery are progressively integrated into supply chain management [7]. Technologies such as the Internet of Things, cloud computing, business intelligence software, predictive analytics, and blockchain are contributing to this transformation. Figure 1 shows diverse supply chain technologies. These innovations have bolstered decision-making in procurement, enabled precise process forecasting, fostered increased transparency, facilitated cost reduction, and enhanced flexibility within the supply chain infrastructure.

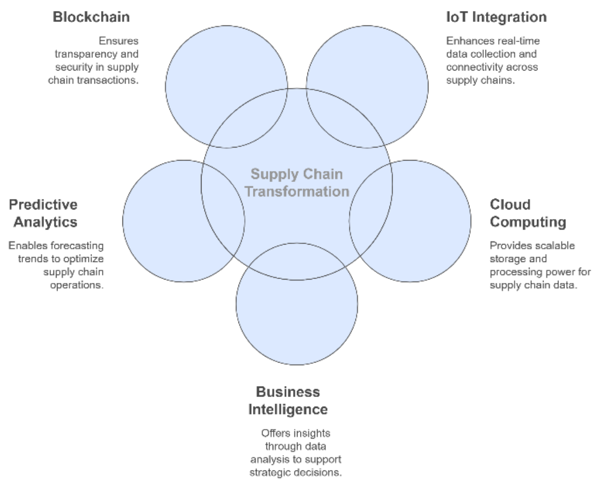

Figure 1: Overview of diverse supply chain technologies, including the Internet of Things, cloud computing, business intelligence, predictive analytics, and blockchain. These innovations enhance decision-making in procurement, improve process forecasting, increase transparency, reduce costs, and provide greater flexibility within supply chain operations.

4. Exploring the Role of Blockchain in the Food Supply Chain

Blockchain represents an inventive technology and serves as a continuous data registration system that verifies and stores information in blocks. Each block within this information chain comprises a transaction list, a digital signature for validating the preceding block, and a data hash. The pivotal characteristic of blockchain lies in its ability to resist easy alteration or deletion of information once stored in a block. The interconnection of blocks means that any modification in one block ripples through others, facilitating the establishment of a transparent, credible, and reliable information chain [8]. Initially designed as the underpinning for digital currencies like Bitcoin, blockchain has diversified its applications across various sectors such as finance, supply chain, healthcare, legal, and beyond. This technology has garnered attention for promoting transparency and trust among individuals and organizations. The security and optimization of blockchain operations entail each block containing diverse information on various transactions and data pertinent to a specific stage. This information is digitally signed, and upon digitalization, the block becomes part of the blockchain, recorded as a node in the distributed network [9]. Every node, representing a participant in the network, maintains a duplicate of the entire blockchain. Utilizing the digital signature of the preceding block and the hash of its information ensures the non-alteration of the new block through encryption algorithms. When a block gains recognition from valid network members, it swiftly disseminates to other nodes, ensuring complete security. This distribution occurs due to the rapid circulation of information within the network. Blockchain's applications extend beyond digital currencies to include equipment procurement and management, validation, real estate cycles, intellectual property management, and electronic voting systems [10]. Blockchain prides itself on high security and data assurance, reducing fraud and enhancing transparency. It facilitates faster data transfer and operates independently of central control. Nonetheless, challenges such as implementation complexity, high power consumption in certain systems, the necessity for specific standards and regulations in certain areas, and concerns related to privacy and access rights present hurdles. Despite these challenges, blockchain, as an innovative technology, has gained recognition for its versatile capabilities across various fields and has found practical use [11].

4.1. The Impact of Blockchain Technology on Food Distribution

Blockchain represents a decentralized and secure digital technology that plays a pivotal role in enhancing the efficiency of the food supply chain. This innovative technology ensures the secure and transparent recording of information pertaining to food production, transportation, storage, and distribution through the use of informational blocks. The ability to permanently and unalterably record data in the blockchain guarantees a high level of transparency and security across all stages of the supply chain [12]. Notably, this technology improves the accuracy of tracking the journey of food items, effectively preventing fraud and unauthorized alterations. The rapid accessibility of information within the blockchain facilitates prompt and precise responses to incidents or safety-related concerns. Furthermore, by enhancing issue detection and management, blockchain contributes to minimizing food waste. To illustrate, envision a food company seeking to trace the trajectory of a batch of its products, such as fresh fruits [13]. Employing blockchain, the company can meticulously record information at each stage, encompassing cultivation methods, harvest dates, transportation conditions, and temperature fluctuations. This data is securely stored in blocks within the blockchain, accessible to all supply chain participants, ranging from farmers to end consumers. Consequently, when a customer buys a food product, like a kiwi, from a grocery store, they can scrutinize the precise path and history of that kiwi—from planting to arrival at the store—by scanning a QR code or digital identifier [14]. This provides the customer with assurance that the product has traversed the supply chain safely and securely, adhering to safety and quality standards at every stage. In conclusion, blockchain offers both organizations and consumers the opportunity to leverage heightened transparency in the supply chain, thereby enhancing the safety and quality of food products.

4.2. The Function of Blockchain in the Food and Biomaterials Supply Chain

Blockchain, emerging as a revolutionary approach to food supply chain management, not only plays a pivotal role in establishing security and transparency but also initiates substantial transformations in the technological processes related to food. This technology furnishes precise and deviation-free information regarding the production, transportation, distribution, and sale of food items. By establishing a secure and entirely transparent digital system, Blockchain provides distinct advantages. Each phase of the supply chain is meticulously documented as encrypted blocks within an independent chain, accessible to all participants with only one immutable piece of information [15]. This guarantees the reliability and credibility of information across every stage of the supply chain. Despite its inherent drawbacks, Blockchain stands as an innovative technology with numerous advantages in the food industry (Figure 2 shows this aspect).

Figure 2: Illustration of the role of Blockchain in the food and biomaterials supply chain

The innovative use of Blockchain in the food supply chain not only reinforces security and transparency but also records each step of the supply chain with encrypted blocks in a secure and transparent digital system, ensuring credibility despite the challenges and limitations it may encounter [16].

4.3. The benefits of blockchain in the food supply chain

4.3.1. Enhanced Transparency and Dependability

Blockchain technology meticulously captures information relevant to each phase of the supply chain, ensuring transparency and reliability. This feature significantly augments consumer confidence in both the production procedures and the inherent attributes of products. By presenting clear-cut information and granting access to the complete history of the consumption chain, blockchain empowers consumers to effortlessly trace the trajectory of each product from its initial production to final delivery. This cultivates heightened assurance among consumers regarding the origin and production conditions of the goods. All stages of production and processing, encompassing agricultural methods, manufacturing processes, and storage procedures, are systematically documented in a transparent manner on the blockchain [17]. This wealth of information equips consumers with the tools to make well-informed decisions. The digital signatures and immutable nature of the information within the blockchain substantially reduce the likelihood of fraudulent activities in these domains, thereby reinforcing trust among participants in the supply chain. Blockchain's user-friendly interface allows consumers to access comprehensive information swiftly. This enables quick scrutiny of product details and facilitates decision-making based on the most recent data. Transparent information related to blockchain has the potential to motivate producers to adopt more sustainable and environmentally friendly practices. Informed consumers, possessing increased knowledge about production methods, actively contribute to the advocacy of sustainable practices [18]. As a result, transparency endows companies with the capability to uphold both quality and competitiveness, ultimately benefiting consumers and catalysing advancements within the industry. The transparency and reliability inherent in blockchain technology contribute positively and serve as distinctive features for numerous established brands in the market, augmenting their credibility and sustainability.

4.3.2. Mitigation of Fraud Risks through Blockchain Implementation

Blockchain, by introducing an unalterable information recording system, is poised to effectively alleviate the vulnerabilities associated with food supply chains. This decrease in fraudulent activities yields advantages for all participants engaged in the supply of goods. The blockchain uniformly logs each transaction and stage of movement, employing encryption algorithms to assure a secure and reliable digital history of products, wherein modifications to information are readily discernible. A distinctive digital signature accompanies each block within the blockchain, serving as an identifier linked to the original data owner's registration of information [19]. This digital signature remains immutable, providing robust protection against potential fraud attempts. In light of data encryption and digital signatures, the secure transmission of information within this framework significantly curtails the likelihood of fraud or unauthorized alterations. Any modification to a block in the blockchain necessitates consensus among all participating entities, guaranteeing that alterations conform to established quality standards and mitigating the potential for fraudulent activities. The heightened transparency within the system facilitates accessible information pertaining to the production, transportation, and processing of products within the automotive industry. Consequently, this engenders consumer trust and diminishes the probability of engaging in fraudulent activities.

4.3.3. Streamlining Supply Chain Efficiency

Immediate and precise information access empowers businesses to enhance assurance procedures, boost efficiency, and curtail waste. The utilization of blockchain notably advances the efficiency and optimization of supply chain management. This advancement, achieved through accessing information and employing accurate analytics, has the potential to streamline processes at various junctures, resulting in waste reduction and heightened efficiency. Blockchain facilitates open and accessible information for all participants involved in the pursuit [20]. This transparency in information accessibility enables employers and decision-makers to make informed decisions based on up-to-date information. Equipped with accurate and real-time data, these systems can directly bring about the necessary performance improvements. This directly translates into improved efficiency, inventory optimization, and reduced lead times. Managers, armed with precise information about inventory levels, storage conditions, and transportation routes, can more accurately predict and reduce waste. This also contributes to the reduction of materials and promotes sustainability [21]. Functioning as a chain of comprehensive historical data, blockchain enhances communication among family members, thereby mitigating optimization challenges, minimizing misunderstandings, and preventing issues associated with incomplete or inaccurate information. In the realm of consumers, the trust among participants holds paramount importance. Blockchain, by establishing a dependable and transparent information system, aids in fostering trust among service participants. By accessing accurate and comprehensive information regarding changes in these processes, managers can enhance risk management and mitigate the impacts of market fluctuations [22].

4.3.4. Enhanced Security Measures

Blockchain, employing encryption and digital signatures, fortifies information security and bolsters cyber resilience. Elevated security stands out as a distinctive attribute of blockchain, as it secures information exceptionally through encryption and digital signatures. Utilizing encryption throughout all stages safeguards data, amplifying the security of sensitive transaction details and personal information. Each block within the blockchain undergoes a transformation into a digital signature, ensuring the preservation of information in its original state by the initial data owner [23]. This digital signature plays a crucial role in verifying the authenticity and integrity of the data. The dissemination of information across the entire network in blockchain complicates the task of a cyber adversary attempting to impact the data at a single point. For intrusion, an attack on multiple network points becomes necessary. Blockchain, capitalizing on the collaboration among network participants, thwarts unintended changes or fraudulent activities. Approval from the majority of participating entities is requisite for any alteration to a block, forestalling unauthorized modifications. The amalgamation of high security measures and the utilization of encryption technologies contributes to an augmented resilience against cyber-attacks in blockchain [24]. Continuous monitoring of information within the blockchain ensures swift detection and appropriate resolution of any undesired changes. Hashes are employed in the blockchain for meticulous verification, uniquely indicating whether data has undergone alteration. Any modification influencing the hash heightens the security status of the information. This combination of security features transforms blockchain into a robust security system, resilient against cyber threats, and particularly valuable in sensitive domains, as exemplified in the instances highlighted [25].

4.4. Disadvantages of blockchain in the food supply chain

4.4.1. Complexity in Implementation

Introducing blockchain into the food supply chain may mandate adjustments to current processes and systems, potentially leading to escalated costs and time investment. The integration of blockchain in the food supply chain, given its technical intricacy and the imperative for modifications in existing processes and systems, may give rise to supplementary expenses and time consumption. The deployment of blockchain might necessitate significant alterations in ongoing processes, conceivably demanding training and educational initiatives for personnel, resulting in endeavours that are both time-intensive and costly. A successful implementation necessitates alignment with both international and national standards, potentially prompting alterations in systems and processes to adhere to blockchain standards [26]. Individuals possessing the technical prowess for blockchain may not be readily accessible within the organization. Training new personnel or enhancing existing capabilities can be a time-consuming and financially burdensome undertaking. Organizational systems and technical infrastructure may require upgrades or adjustments to synchronize with blockchain, potentially demanding additional investments and time. The secure and transparent exchange of data among chain members can yield valuable insights. Ensuring the security and precision of data transfer is paramount, requiring a meticulous examination and resolution of technical challenges. Some members of the community may find themselves intricately involved in the implementation of blockchain. The active participation of all members is indispensable for the success of the project [27]. The implementation of blockchain may encompass supplementary costs, encompassing expenses related to training, technical modifications, new infrastructure, and the costs associated with adjustments in processes. Some systems and software within the chains may not be inherently compatible with blockchain and may necessitate integration and modification.

4.4.1. Legal Challenges and Standards

The legal standards associated with blockchain in the food supply chain remain incompletely defined, potentially resulting in legal challenges and discord among stakeholders. Implementation hurdles arise from legal concerns and breaches of established standards in deploying blockchain within the food supply chain. The application of blockchain for public data sharing may impinge upon individual privacy, thereby contravening privacy laws and precipitating legal complications. The critical right of determining legal responsibility in cases of failures or errors within the blockchain poses a significant challenge [28]. Addressing responsibility and compensation in the event of problems can be intricate. Blockchain implementation may necessitate adherence to both national and international laws, and the absence of common standards and regulations across different nations can give rise to legal disputes. Intellectual property rights issues also present a legal challenge within the realm of blockchain. The permanence and irreversibility of information changes in blockchain may have implications for intellectual property rights. The effective utilization of blockchain demands precise legislation pertaining to the nature of data and information within the blockchain. Discord on this matter has the potential to escalate into legal disputes. The malleability of contracts and agreements within blockchain can evolve into projects and legal complications [29]. In the case of involvement with foreign companies, consideration of international legal laws is imperative. Disputes related to data sharing may lead to legal conflicts. The establishment of suitable legal standards and regulations for the integration of blockchain in the food supply chain is indispensable for mitigating legal disputes and fostering an environment conducive to collaborative improvement [30].

4.4.2. Energy Consumption Challenges

Certain blockchains necessitate a considerable amount of energy for executing the mining process, posing potential environmental concerns. The high energy consumption associated with specific blockchains presents a noteworthy challenge. The majority of blockchains operate on mining algorithms tailored for intricate computations involved in block creation. This computational procedure, commonly referred to as "proof of work," demands substantial processing power, resulting in a significant energy footprint [31]. Inappropriate utilization of energy resources and the resultant heightened energy consumption have the potential to adversely impact the environment. Elevated energy consumption may contribute to the emission of greenhouse gases and exacerbate climate changes, particularly given the reliance on fossil fuels in many mining-related energy sources. The mining process necessitates high-performance hardware for both production and conversion, leading to escalated energy consumption and more pronounced environmental consequences [32]. Concerning the substantial energy requirements, certain blockchains may influence alterations in sustainability principles and environmental concerns. Some blockchains resort to fossil energy sources like carbon, natural gas, and other pollutants to mitigate environmental damage. In response to this challenge, certain blockchains are exploring alternative methods such as "proof of stake," characterized by lower energy consumption and a reduced environmental footprint. Moreover, the adoption of renewable energy sources presents itself as a viable solution to mitigate the high energy consumption associated with specific blockchain implementations.

5. Smartening the food industry

In recent decades, groundbreaking progress in cutting-edge technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Business Intelligence (BI), and cloud computing has emerged as pivotal instruments for elevating the operational efficiency of the food industry. This integration of technologies facilitates the intelligent automation of food production units, resulting in reduced costs, heightened productivity, and improved product quality. In the production, storage, and transportation processes, the IoT employs sensors and internet-connected devices, streamlining the collection of extensive, real-time data. This data offers invaluable insights into production conditions and the quality of food materials [33]. The utilization of AI algorithms in analyzing IoT data underscores the importance of predicting market demands, optimizing supply chains, and enhancing automation within production lines as essential steps in the intelligent transformation of the food industry. The concept of cloud computing revolves around the perpetual sharing of computational resources and data through the internet with high efficiency. This capability proves significant for the food industry, given the necessity to process voluminous data, improve flexibility, and reduce IT infrastructure costs. Furthermore, Business Intelligence systems play a crucial role in dissecting collected data, delivering decision-making information to various stakeholders within the organization [34]. These pieces of information can significantly contribute to refining decision-making processes and resource management within the food industry. The amalgamation of the Internet of Things, Artificial Intelligence, Business Intelligence, and cloud computing in the food industry holds the potential for remarkable enhancements and transformations across diverse domains. The intelligent automation of this industry not only aids in efficiency and cost reduction but also enables swift responsiveness to market fluctuations and customer needs. Subsequent sections will delve into a comprehensive examination of each of these intelligent technologies.

5.1. Internet of Things

The term Internet of Things (IoT) denotes the communication among computational, mechanical, and digital devices over the Internet without requiring human intervention. These devices integrate intelligent components for establishing communication with a central system and collecting/sending data from their surrounding environment. The data gathered by sensors is contingent on the device's type and function. Devices selectively acquire essential data to perform specific actions, aiding in decision-making [35]. For example, sound sensors gather data related to fluctuations in sound levels and transmit it to the data processing center to gauge the ambient noise level. Essentially, the aim of the Internet of Things is to streamline communication and interaction among network-connected devices by establishing a link between sensors and devices via the Internet. Users, in return, possess the capability to observe and manage equipment. The Internet of Things is a technology designed to enhance people's intelligent living and facilitate more convenient control over various aspects of their lives. Nonetheless, the effectiveness of this smart automation lies in its ability to simplify tasks rather than introducing additional complexity [36]. Precision and speed in task execution hold significant importance today, prompting increased interest in technologies such as IoT. The Internet of Things imparts intelligence to objects by enabling them to concurrently receive or transmit data, empowering them to execute automated tasks with minimal human intervention. The Internet of Things embodies a layered architecture encompassing diverse devices and objects that can communicate through a mechanism known as Machine-to-Machine (M2M) communication. The architecture of the ecosystem enables real-time data transfer with limited human involvement [37]. Each stratum within this ecosystem is assigned specific responsibilities, to be expounded upon subsequently. The sensor layer stands out as the paramount element in Internet of Things (IoT) technology, encompassing sensors integrated into devices. These sensors establish communication with the physical environment, detecting and recording alterations in the surrounding milieu. They amass and store data [38].

For instance, GPS sensors trace positional information to ascertain details such as the distance to the destination and the most efficient route. The ensuing layer is the network layer, tasked with the transmission of information from sensors and devices to platforms and cloud centers. Internet of Things devices employ diverse methods for connectivity and data sharing. The majority utilize wireless connections, such as Wi-Fi, Bluetooth, or even Ethernet in residential and office settings, while certain devices may utilize LTE or satellite connections for communication [39]. The succeeding layer is the data processing stratum, charged with the processing of the IoT ecosystem. Servers process data acquired from sensors using artificial intelligence algorithms. Following data collection, the information is conveyed to the cloud infrastructure via a gateway. Subsequently, requisite instructions are dispatched to actuators to execute operations on this data. The obtained outputs are harnessed for subsequent decision-making. The ultimate layer is the application stratum, directly interfacing with the user. It encompasses the user's graphical interface with the Internet of Things network. Devices such as smartwatches, televisions, and smartphones interact with this layer, each serving a distinct purpose in attaining specific objectives [38-40].

5.2. Leveraging Artificial Intelligence for Improving the Efficiency of Food Production and Consumption

Artificial intelligence plays a pivotal role in augmenting efficiency and streamlining production and management processes within the food industry. By employing AI algorithms and models, this technology facilitates the precise analysis of extensive and intricate data pertinent to the food supply chain. Herein, we explore some of the advantages associated with the integration of artificial intelligence in this sector. Robust AI algorithms conduct a comprehensive analysis of the entire supply chain, encompassing the comprehension of market trends, forecasting requirements, and optimizing distribution routes. This optimization yields reductions in lead times, cost minimization, and an overall enhancement in supply chain efficiency [41]. AI is proficient in scrutinizing market patterns and fluctuations, aiding in the comprehension of requirements and effective market utilization. Through the thorough examination of vast and intricate data, AI enhances demand forecasting—a notable strength of this approach that contributes to optimal inventory adjustments and resource utilization. Artificial intelligence algorithms, in their analysis of distribution routes, strive for continual optimization, ultimately resulting in reduced transportation costs. The amelioration of supply chain optimization leads to reduced costs associated with materials, transportation, and inventory management.

This cost reduction facilitates companies in enhancing their competitiveness and profitability. Artificial Intelligence (AI) serves as a catalyst, elevating the overall efficiency of the supply chain. This advancement results in improved services, heightened quality, increased satisfaction, and fortified brand presence. An instrumental role of AI in advancing the food supply chain lies in its ability to predict food product consumption. This functionality empowers users with algorithms and predictive models that harness the precision of AI in analysing extensive and intricate datasets [42]. The analysis aids in recognizing diverse market patterns and supporting various market factors. Furthermore, the utilization of predictive algorithms and models allows for precise predictions of food product consumption. This predictive insight facilitates superior inventory management and planning. Augmented predictive capabilities empower companies to optimize existing products, leading to cost reduction and vulnerability prevention. It also equips companies with a deeper understanding of the market, enabling them to deliver products at the right time and place based on products and associated services [43]. AI assists companies in enhancing service relationships and adapting to rapid changes in market conditions, limitations, and challenges. The integration of AI in the food supply chain can contribute to minimizing food consumption and streamlining production processes.

Analysing information allows supply chain managers to identify regions with the highest waste and implement necessary improvements. By scrutinizing consumption patterns in production processes, AI aids in reducing the consumption of raw materials. This refinement results in waste reduction and a decline in costs associated with material procurement. Early detection of waste-related patterns enables AI to prevent waste by optimizing production processes, inventory management, and equipment utilization. The reduction in waste leads to a decrease in costs related to disposable materials [44]. This cost-saving enables companies to enhance production efficiency and achieve greater profitability. Through streamlined management and waste reduction, it contributes to environmental sustainability, thereby safeguarding the environment and mitigating the negative impacts associated with food waste. The application of artificial intelligence (AI) techniques in waste reduction equips companies with the capability to exert more sustainable control over natural and environmental concerns. Furthermore, AI augments the oversight of product quality from the production phase to distribution. This capability is facilitated by employing sensors and leveraging supply chain data, leading to a continuous enhancement of product quality. Sophisticated sensors are employed for monitoring production processes, providing immediate and accurate information on product quality, thereby aiding in error identification. The meticulous analysis of sensor data not only improves product quality but also helps prevent errors and defects in the production process. This ongoing refinement in product quality is facilitated by optimizing production functions based on sensor data. In the scrutiny of supply chain data, artificial intelligence discerns processes related to quality control, empowering managers to exercise control over each stage of distribution and production [45].

Through the examination of quality patterns, artificial intelligence can propose enhancements for production processes and quality control. These suggestions foster continuous improvement and heightened efficiency. AI systems excel at offering optimization recommendations for both production and management processes. These recommendations stem from accurate data and business pattern analysis, aiding in the identification of trends, strengths, weaknesses, opportunities, and production-related factors. By scrutinizing and interpreting data, improvement recommendations can be extended to production providers, resulting in increased efficiency, cost reduction, and improved output quality. AI systems can ascertain production pathways, enhance efficiency, anticipate issues during progress, and offer delivery recommendations, thereby bolstering system reliability. AI systems, equipped with machine learning capabilities, exhibit prompt adaptability to market changes and new conditions. This adaptability assists organizations in navigating challenges and furnishes optimal recommendations through data analysis [46]. Artificial intelligence, leveraging machine learning algorithms and neural networks, can swiftly adapt to market dynamics, needs, and challenges, thereby fostering heightened agility and flexibility within the supply chain. The integration of artificial intelligence in the food industry opens up avenues for increased efficiency, cost reduction, and improved product quality. Functioning as a pivotal tool, this technology enhances both the supply chain and production processes in the contemporary world.

5.2.1 Food security and artificial intelligence

Artificial intelligence (AI) assumes a critical role in the domain of food security, empowering the identification of safety-related risks. Recent years have seen significant technological advancements in the food safety industry. The amalgamation of artificial intelligence and machine learning holds the promise of a transformative evolution in the food safety inspection procedures. By incorporating AI and machine learning, safety inspections stand to achieve greater precision, efficiency, and cost-effectiveness [47]. This paper delves deeper into investigating the interconnection between artificial intelligence and food security.

5.3. Data Analysis in the Context of Artificial Intelligence

Artificial Intelligence (AI) exhibits a refined capability for detailed scrutiny of data within the supply chain domain. This analytical prowess contributes to the discernment of undesired patterns, anomalous fluctuations, and hazards linked to the safety of food materials. AI assumes a pivotal role in acknowledging its significance within the food supply chain. Through the utilization of algorithms and machine learning models, AI facilitates the prompt detection of undesirable alterations, thereby mitigating the risk of fraudulent activities in food processes. These systems are adept at executing monitoring processes intelligently and autonomously [48]. Notably, smart sensors and devices are capable of overseeing product storage conditions and discreetly issuing alerts pertaining to specific constraints. The analysis of both historical and current data enables AI to forecast potential instances of food safety breaches, thereby empowering organizations to proactively implement necessary measures. Additionally, AI's capacity to scrutinize communications among diverse variables and parameters in the supply chain aids in identifying unconventional associations that may signal food safety risks. Furthermore, specialized data analysis in the respective field can contribute to the identification and assessment of potential risks related to food safety. This proactive risk identification equips organizations with the means to enhance preventive initiatives and strategies for risk management.

5.4. Predictive Analysis of Risks

Artificial intelligence algorithms, by rigorously scrutinizing both historical and contemporary data, have the capacity to predict potential hazards within the supply chain. This pivotal capability enables organizations to bolster preventive measures well in advance of any impending hazards. AI algorithms possess the capability to dissect market trends and fluctuations, taking into account a myriad of economic, social, and political dimensions. This comprehensive analysis allows organizations to anticipate potential risks stemming from shifts in the market landscape. Through the examination of data pertaining to prices and market fluctuations, AI algorithms can project the potential impact of price fluctuations on the supply chain [49]. This forecasting affords organizations the opportunity to institute effective programs for the management of price-related risks. In a meticulous analysis of supply chain data, covering aspects such as production, transportation, storage, and distribution, AI algorithms can discern specific patterns and unusual changes that may signify potential food safety hazards. Furthermore, AI can accurately predict fluctuations in demand by analysing market demands.

This information serves organizations in optimizing both production and the supply chain in alignment with anticipated demands. By methodically scrutinizing production processes, AI algorithms can pinpoint potential issues in various production stages, furnishing organizations with the capacity to proactively enact corrective strategies [50].

5.5. Fraud Detection

The utilization of artificial intelligence in scrutinizing behavioural patterns and unconventional shifts proves highly effective for detecting fraud within the food supply chain. This discernment process plays a pivotal role in thwarting the infiltration of fraudulent products into the market. Artificial intelligence exhibits the capacity to analyze both typical and atypical patterns within the production processes of goods. Any deviation from established norms in patterns or behaviors may signify a potential risk of fraud. Furthermore, AI can oversee details regarding routes, transportation conditions, and delivery schedules in the transportation of food products [51]. Noteworthy alterations in these aspects may serve as indicators of fraudulent activities. Through an examination of consumer purchasing and consumption patterns, artificial intelligence can identify irregular consumption behaviors, marking them as potential signals of fraud within the supply chain. Additionally, by comparing historical data related to products and production processes, AI can identify any unusual changes or distinctions that may serve as indications of fraudulent activities.

5.6. Precision Monitoring

Artificial intelligence (AI) systems, endowed with sophisticated tracking functionalities, play a pivotal role in achieving meticulous product tracking from the manufacturing phase through consumption. These systems furnish transparent information spanning various phases of the supply chain. Such capabilities empower organizations to promptly address any errors or risks that may manifest within the food supply chain [52]. They proficiently trace the production trajectory of goods from initiation to completion, facilitating the identification of any inconsistencies or flaws in the production process. Through the analysis of product transportation data, AI systems endow organizations with the ability to scrupulously monitor storage and transportation conditions. These systems deliver real-time updates, promptly alerting organizations to any arising issues. AI ensures swift monitoring of product inventory in warehouses and retail outlets, guaranteeing that inventory levels align seamlessly with consumer demand. Additionally, artificial intelligence leverages sensor data and environmental information to issue alerts when storage and transportation conditions of products approach potentially hazardous thresholds [53]. By scrutinizing consumer purchasing and consumption patterns, artificial intelligence (AI) systems offer organizations accurate insights into market preferences and requirements. Through the examination of data gleaned from sensors, AI discerns patterns and essential information, facilitating an understanding of normal conditions and the identification of potential risks. Upon detecting any violations or hazardous situations, the AI system automatically triggers alerts, ensuring swift communication to relevant authorities [54]. Through thorough data analysis, AI systems can proactively tackle potential issues, thereby mitigating risks and elevating product quality and security. Artificial intelligence exhibits the ability to swiftly adapt to changes in the environment. In the event of alterations in environmental conditions or market needs, the system responds promptly.

5.7. Crisis Management

During periods of crisis, artificial intelligence empowers organizations to swiftly and effectively address the causes and consequences of food crises. Artificial intelligence can expeditiously analyse data related to the crisis, detecting undesirable patterns, as well as abrupt surges in demand or declines in production. Employing data analysis and predictive algorithms, artificial intelligence can foresee the secondary repercussions of a crisis and devise emergency plans to mitigate these impacts. In critical situations, artificial intelligence, informed by data analysis and predictions, can facilitate informed decision-making to implement emergency plans and engage with diverse centers. Artificial intelligence assumes a pivotal role in crisis management, overseeing communication strategies and community engagement [55]. This technology aids in crafting intelligent and succinct messages and announcements. Through thorough data analysis, artificial intelligence excels at identifying and prioritizing crisis areas, optimizing the distribution of assistance and enhancing the efficiency of crisis management. Additionally, artificial intelligence contributes significantly to the identification and prevention of disease transmission by ensuring food safety and collaborating with healthcare resources.

5.8. Preventing Disease Transmission

Artificial intelligence plays a pivotal role in swiftly identifying the origins of diseases and mitigating their transmission to humans. Leveraging data from wildlife monitoring, this system identifies disease sources within animal populations, thereby averting transmission to humans. With the support of artificial intelligence, alterations in agricultural and livestock conditions are vigilantly monitored in a precise and timely manner, preventing the occurrence and transmission of diseases to humans. Artificial intelligence's involvement in detecting fraudulent activities in food products is crucial for averting disease transmission through contaminated food items [56]. The implementation of artificial intelligence in the food supply chain enables the rapid and accurate identification of disease sources, thereby thwarting their transmission to surrounding environments. The analysis of data collected from diverse sources contributes to enhancing public health management and preventing disease transmission. Artificial intelligence also plays a significant role in information management within high-risk environments, offering preventive measures against the transmission of viruses and diseases through contact with animals or various surfaces.

5.9. Automating Monitoring Processes

Artificial intelligence facilitates the intelligent automation of monitoring processes within the supply chain. This technology utilizes sensors and supply chain data to intelligently and automatically streamline monitoring processes. Various sensors are deployed to monitor different points in the supply chain, including those measuring temperature, humidity, pressure, and other parameters, ensuring precise monitoring of environmental and transportation conditions [57]. By analysing data collected from sensors, artificial intelligence identifies patterns and critical information, contributing to an understanding of normal conditions and the identification of potential risks. Upon identifying any violations or hazardous situations, the artificial intelligence system automatically activates alerts, which can be promptly communicated to relevant authorities. Through meticulous data analysis, artificial intelligence systems proactively address potential issues, thereby reducing risks and improving the quality and security of products. Artificial intelligence possesses the capability to swiftly adapt to changes in the environment, reacting promptly in the face of alterations in environmental conditions or market needs.

5.10. Cloud computing

Cloud Computing represents a methodology for providing computational services that encompasses servers, storage space, databases, networks, software, analytics, and information through the internet. This approach facilitates users in conveniently and cost-effectively accessing the computational resources they require, eliminating the need for the procurement and maintenance of hardware and software [58]. Notably, cloud-based storage offers the flexibility of remotely storing files in a database as opposed to relying on dedicated hard drives or local storage devices. The adoption of cloud computing allows for data and software application accessibility from any location and at any time through internet connectivity. The prominent advantages of cloud computing, contributing to its widespread adoption among users and businesses, include cost-effectiveness, heightened productivity, accelerated speed, enhanced efficiency, superior performance, and robust security. The term "cloud computing" is coined due to its capacity to provide access to information within a virtual or cloud space. Companies providing cloud services empower users to store their files and applications on remote servers, enabling convenient access to information via the internet at their discretion [59]. This implies that users are not restricted to a specific location for data access, and they can effortlessly oversee and manage their stored data remotely. Cloud computing efficiently handles resource-intensive data processing tasks, offloading these operations to remote computers in virtual space. Consequently, the internet undergoes a transformation into a cloud space, facilitating universal access to data and files from any location worldwide using any device.

5.10.1. The role of cloud computing in food distribution

Cloud computing is a technology facilitating the delivery of computational resources, data storage, and diverse services over the internet. Within the domain of food distribution, cloud computing assumes a pivotal role in improving processes and optimizing operations. Its implementation in the food distribution sector aids organizations in achieving more agile and efficient responses to market dynamics and fluctuations in demand, with the ultimate goal of attaining optimal performance within the supply chain [60].

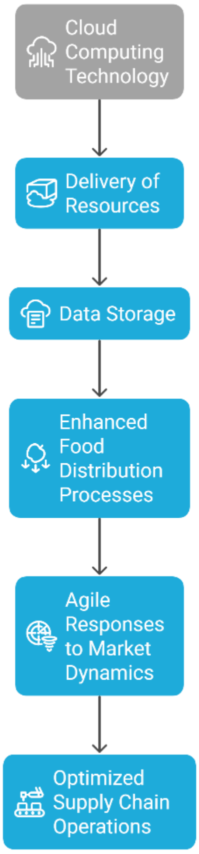

Figure 3: The role of cloud computing in food distribution, illustrating how it enhances agility and efficiency in supply chain operations.

This matter has been examined in Figure 3. By offering computational resources and storage through the internet, the adoption of cloud computing in food distribution enables companies to swiftly adjust to changes in market conditions and variations in demand, thereby enhancing and optimizing supply chain operations. The subsequent sections elaborate on some of the key functions of cloud computing in the realm of food distribution.

5.11. Supply Chain Management

Cloud computing provides access to interactive Supply Chain Management (SCM) systems. This allows supply chain managers to receive real-time updates on inventory, orders, and distribution routes. When cloud computing is employed in supply chain management, it enables managers to access SCM systems online and remotely. This access empowers them to quickly receive and implement real-time updates regarding product inventory status, newly received orders, and optimal distribution routes [61]. In other words, with the use of cloud computing, supply chain managers are no longer required to be physically present at the system location or restricted to a specific place. They can connect to the SCM system and its information from anywhere with internet access, allowing them to implement the necessary updates. This capability grants managers the flexibility to respond more accurately and swiftly to market changes, demand variations, or immediate situations, executing optimal optimization decisions within their supply chain [62].

5.12. Data Analysis

The utilization of cloud computing facilitates the storage and processing of extensive datasets. Through accurate examination of data pertaining to demand, inventory, and system performance, the realm of decision-making in food distribution experiences significant enhancements. Cloud computing, when applied to data analysis, affords us the efficiency to handle vast data volumes with high performance, enabling swift data access and analysis [61-63]. By conducting meticulous analyses of data concerning product demand, inventory levels, and distribution system performance, diverse patterns and valuable insights can be unearthed. For example, demand analysis aids in comprehending when and where there is an upsurge in product demand, information crucial for effective inventory planning and distribution. Moreover, a comprehensive evaluation of inventory and system performance serves as a guide for optimizing distribution processes. Continuous monitoring of real-time system performance empowers us to introduce ongoing improvements, culminating in reduced costs and heightened efficiency in food distribution. In summary, the integration of cloud computing into data analysis equips us to make more informed and efficient decisions in the management and enhancement of food supply chain performance.

5.13. Business intelligence

Business Intelligence (BI) refers to the knowledge derived from the analysis of data within a company or organization. This process provides practical information to managers and business owners. BI, with the assistance of this data, offers cohesive and valuable insights into the performance of various sections of an organization or company, the volume of purchases and sales, influential factors affecting organizational activities, and more. This information aids business managers in decision-making processes. Additionally, BI systems provide solutions for changing the current situation and achieving faster capital returns [64]. In essence, Business Intelligence acts as a practical advisor for businesses, elucidating past, present, and future profitability through real figures. BI furnishes efficient and valuable solutions to maximize overall profits. The significance of Business Intelligence lies in its ability to spare organizations or companies significant time and human resources required for manual examination of their profitability and performance. In such manual approaches, businesses encounter incomplete and ineffective information. Conversely, Business Intelligence can rapidly present accurate information and statistics on the performance of companies within a short timeframe [65]. Business Intelligence focuses on various factors such as purchase and sale volumes, dates, times, environmental factors, and more, before delving into data interpretation. For instance, it analyzes which products people in a region purchase more and which products have limited demand among the residents of a city. These data and insights assist business managers in making more informed decisions regarding investments in their products and services, as well as the optimal timing and methods for their presentation. There are no constraints on the use of Business Intelligence systems; any business with comparable and measurable information, or the need for precise and comprehensive data on its capital and profits, can benefit from this system. In Business Intelligence, information for each organization must be understandable and analyzable for the management team [66]. Hence, it is advisable for the leadership team in any organization to delineate the manner in which information should be accessible to them. Once the company's expectations are clarified, the BI implementation team should proceed to devise specific dashboards and formats. For instance, the methodology through which managers retrieve reports is formulated and executed during this stage. Within Business Intelligence systems, the method of data collection holds significant importance, necessitating the proper provisioning of all data to this system. Business Intelligence is crafted to center on predictive modeling, scrutinizing vulnerabilities, and comprehending the factors influencing business profitability and losses. Consequently, it is more effective to institute a centralized data repository, fostering interaction between this section and other organizational departments [67]. This approach ensures that data from all departments is consolidated and readily accessible in a dedicated location. At this juncture, the proposed blueprint within the Business Intelligence system should undergo experimental implementation and practical utilization. Despite the deployment of the most precise plans and formulas in this system, the prospect of encountering issues and errors is not unforeseen. Hence, this phase warrants repetition to attain the desired outcome by minimizing errors. In the conclusive stage, the outcomes of the assessments are determined, and the system consistently integrates updated information into its existing dataset. Access to BI system reports is facilitated online [68]. Concerning the impact of Business Intelligence on food distribution, it can be asserted that Business Intelligence (BI) leverages data analysis and information pertinent to food distribution as a pivotal instrument for streamlining processes in the supply chain. This technology enables meticulous monitoring of inventory levels, examination of demand patterns, and furnishes recommendations for enhancing performance and efficiency in food distribution. By delivering precise and timely information, Business Intelligence contributes to strategic decision-making aimed at refining distribution processes and curtailing expenses. Additionally, it expedites the augmentation of service quality to customers and ensures a swifter response to market demands [69].

6. Conclusion

The integration of Artificial Intelligence, Blockchain, and the Internet of Things presents a ground-breaking opportunity to revolutionize food supply chain management. By harnessing the strengths of each technology, the industry can achieve unprecedented levels of efficiency, transparency, and security. AI enhances decision-making and reduces waste, while Blockchain builds trust through its immutable records, ensuring traceability and combating fraud. IoT brings real-time data to the forefront, enabling agile responses to emerging challenges. Together, these technologies create a more resilient food distribution system, better equipped to navigate the complexities exposed by global crises such as the COVID-19 pandemic. However, realizing their full potential requires addressing existing challenges, including Blockchain's energy demands and regulatory uncertainties. As we move forward, stakeholders must collaborate to overcome these barriers, ensuring that the food supply chain not only adapts to contemporary demands but also paves the way for a sustainable and secure future. Embracing this technological convergence will not only benefit producers and consumers alike but will also contribute to a more robust global food system.

Availability of data and materials

The datasets supporting the conclusions of this study are included within the article.

Competing Interests Statement

The authors have declared that no competing interests.

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