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DEVELOPMENT OF AI-DRIVEN PREDICTIVE MODELS AND IOT-BASED SOLUTIONS FOR ENHANCING FOOD QUALITY AND SAFETY IN SUPPLY CHAINS

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Abstract:
The global food supply chain is under pressure to address critical issues such as maintaining food quality, ensuring safety, and reducing waste. This paper delves into the transformative role of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in improving food quality and safety throughout supply chains. AI-powered predictive models, leveraging machine learning algorithms, are employed to evaluate food shelf life and enhance operational efficiency. Meanwhile, IoT-based innovations, such as cost-effective sensors and real-time monitoring systems, contribute to traceability and adherence to quality standards. The integration of blockchain technology for secure data handling is also explored, offering greater transparency and traceability. Through case studies and proof-of-concept applications, the paper highlights the practical use and advantages of these technologies in real-world contexts. The discussion concludes by addressing challenges, such as costs, the need for technical expertise, and regulatory compliance, while pointing toward future research opportunities to foster sustainable and resilient food supply chains.

Keywords: AI-powered predictive models, IoT innovations, food quality, food safety, supply chain optimization, machine learning, blockchain integration, traceability, real-time monitoring, food waste reduction

1. Introduction

Food is a critical part of our daily lives and social activities. People not only care about how much food is available but also place high importance on food quality and safety. These expectations have been rising over years along with consumers' increasing purchasing power. On the other hand, there is a growing demand for global food distribution since agricultural products are usually not produced at places where they are needed due to climatic conditions. The combination of consumers' rising expectations and the global food supply brings challenges to food quality and safety [1]. Unfortunately, foodborne illnesses still occur and therefore food recalls and litigation

are required. Approximately 76 million people get ill from 325 thousand reported foodborne disease outbreaks, 5000 die and 300 million dollars food recalls annually.

Meanwhile, in the EU, 25 thousand reported cases of foodborne illnesses occur annually with more than 50 percent related to non-specified foods, most likely due to a long non-transparent food supply chain. Because of consumers' increasing awareness of food quality and safety, the food supply chains are desired to be more transparent, traceable and controllable. Transparency is particularly important for high-value processed food such as organic food or food with specific continental or geographical origins. Currently, up to 30-40 percent of food is wasted at some stage of the supply chains in both developed and developing countries. Food wastage is severely detrimental to the economy, environment and society. The Global Food Loss and Waste Protocol launched by the EU aims to halve the food waste by 2025. Therefore there is a pressing need to transform the food supply chains to keep food quality and safety and reduce food wastage.

Advances of the Internet of Things (IoT) and artificial intelligence (AI) technologies in recent years have made it possible to significantly transform food quality and safety in the food supply chains [14]. IoT devices can collect diversified data related to environmental and biological conditions throughout food supply chains, while AI can model complex relationships among the collected data and outputs. The co-development and integration of AI driven predictive models and IoT based solutions can provide new means to monitor, control and even guarantee food quality and safety in the food supply chains. Meanwhile, other aspects of food supply chains such as food wastage and energy consumption can also be monitored and minimized by technology development.

This paper is aimed at introducing the AI driven predictive models and IoT based solutions co-developed for the food supply chains to enhance food quality and safety as well as minimize food wastage and energy consumption.

1.1. Background and Significance

Food quality and safety have always been a significant concern for human beings. Historical records indicate that efforts to maintain food quality and safety date back thousands of years. For instance, ancient laws, such as the "Code of Hammurabi" around 1700 BC, imposed penalties for poor food quality. Over time, countries enacted laws and established institutions to ensure food quality and safety. Technological advancements have played a crucial role in maintaining food quality and safety standards in the food supply chain. For example, the establishment of the "Food and Drug Administration (FDA)" in the United States in 1906 was a significant milestone in ensuring food quality and safety [1]. The basic approach of the food supply chain had remained unchanged for a long time. However, over the past few decades, several high-profile food quality and safety incidents have raised doubts about the effectiveness of traditional food supply chain practices. For instance, food safety incidents involving spinach, peanuts, and eggs in the United

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States led to illnesses in thousands of people, and some even died [2]. Similarly, a series of food safety incidents in Europe damaged the reputation of several food companies.

With the growing awareness of food quality and safety issues, consumers have become more educated and concerned. This heightened awareness has resulted in increased vigilance, especially regarding the sources of food products. Many consumers now actively seek more information about the foods they purchase. They question the processes used to produce, process, and distribute food and their implications for quality and safety. As a result, transparency in food production and supply is currently in great demand. Several countries have recently passed laws to implement traceability systems for food production and processing. Unfortunately, many small food businesses lack the resources needed to comply with complex traceability requirements. Furthermore, food industries are facing increasing regulatory pressures to comply with stringent food quality and safety regulations. For example, the "Food Safety Modernization Act (FSMA)" emphasizes the need for proactive measures to improve food safety, placing the responsibility for food safety on food manufacturers/processors.

The importance of food quality and safety is being ignored in developing countries, although growth is often witnessed in food supply chains. With all the concerns regarding food safety and quality, there is a dire need for new innovative solutions that can help improve the food quality and safety throughout the food supply chains. The advent of Artificial Intelligence (AI) and the Internet of Things (IoT) technologies, coupled with the need for transparency in food supply chains, can provide the foundation for the development of new innovative solutions.

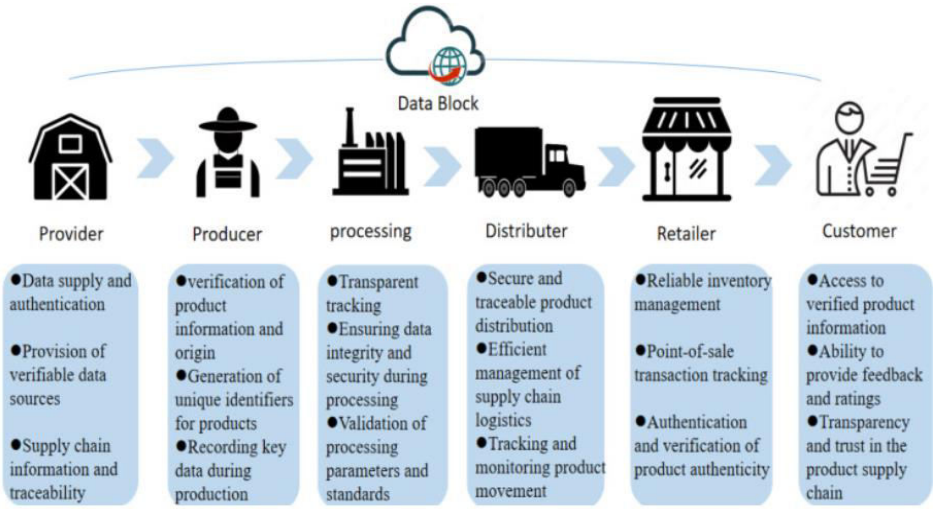

Figure 1:AI and IoT Technologies for Revolutionizing Food Quality and Safety in Supply Chains

AI and IoT technologies have the potential to revolutionize how food quality and safety are ensured throughout the food supply chains. These technologies can dramatically change the current state of affairs by enabling proactive, adaptive, and scientific risk-based solutions. This research intends

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to develop AI-driven predictive models and IoT-based solutions to ensure food quality and safety throughout the food supply chains [14].

1.2. Research Objectives

To tackle the challenges in food safety and quality, this thesis proposes to explore a reference architecture that combines IoT sensing devices, artificial intelligence (AI)-based models, and blockchain technology, focusing on monitoring temperature-sensitive food products in the supply chain. The specific objectives of the research are as follows:

1. To investigate AI-driven predictive quality models using machine learning regression algorithms for assessing the remaining shelf life of food products based on temperature history. The performance of the models will be evaluated and validated using two datasets: laboratory-scale data on the pasteurization of milk and industrial-scale data on the distribution of yogurt.
2. To develop IoT-based solutions consisting of low-cost wireless sensors, a cloud-based gateway, and a web-based application for monitoring food quality and safety in the supply chain. The solutions will be thoroughly tested in laboratory and industrial environments, focusing on their applicability for small and medium-sized enterprises.
3. To explore the integration of AI-driven predictive models in IoT-based solutions to provide food quality information to the supply chain actors in real time. A proof-of-concept implementation will be presented, illustrating model integration in a web-based application with a focus on yogurt as a temperature-sensitive food product.
4. To examine the integration of blockchain technology in IoT sensing devices and AI model-based food quality and safety monitoring solutions. A proof-of-concept implementation will be presented, focusing on the use of smart contracts for tracking the transfers of IoT sensing devices along with food products in the supply chain and the AI model-based quality assessment of food products.

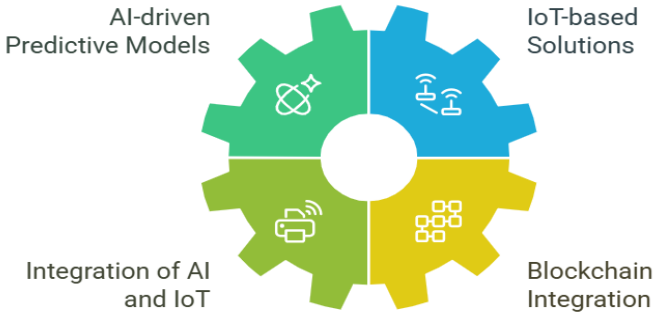

Figure 2:Architecture for AI-Driven Predictive Models and IoT-Based Solutions in Food Supply Chains

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2. Fundamentals of AI in Food Quality and Safety

Artificial intelligence (AI) has the potential to transform the food industry, enhancing food quality and safety. A profound understanding of essential AI concepts, such as machine learning (ML) and deep learning (DL), is critical for successful food quality and safety solutions. ML and DL methodologies can process large datasets from various sources, and generate actionable insights. By deploying predictive models, AI can empower industries to proactively monitor and mitigate food safety risks. There are various potential AI applications, such as predictive analytics, risk identification, quality monitoring, and design optimization. AI technologies have been implemented in the food industry to improve operational efficiency, enhance food quality, and ensure food safety. For example, a bakery chain developed an AI solution to predict the quantity of bakery products to be produced for each shop to optimize inventory management and minimize waste [1]. Another AI application employed computer vision technology to evaluate food quality automatically during the food processing stage. The processed products are classified as defective or non-defective according to pre-set standards, which minimize the need for human quality control. AI technologies can also be applied to track food fraud in the supply chain.

Minimizing food waste throughout the supply chain is another critical need that AI could address. An AI-based model was developed to enhance the performance of a food processing line while considering energy consumption and food waste. To achieve this, data-driven DL models were first established using historical data to predict benchmark performance. Then, optimization approaches were implemented to determine the set points of the control strategy that minimize food waste. By combining ML methods and process data, food traceability technology was developed based on the whole food supply chain to identify producers by tracking food characteristics. There is also the potential to combine AI systems and blockchain technology to enhance food traceability. To successfully implement AI applications in food quality and safety, it is critical to maintain the integrity and quality of the data used. With a basic understanding of AI technologies, food scientists can undertake significant digital transformation efforts to develop AI-driven solutions for food quality and safety. Recently, there has been an increasing number of AI applications in the food industry related to quality monitoring, safety control, and chain traceability [3].

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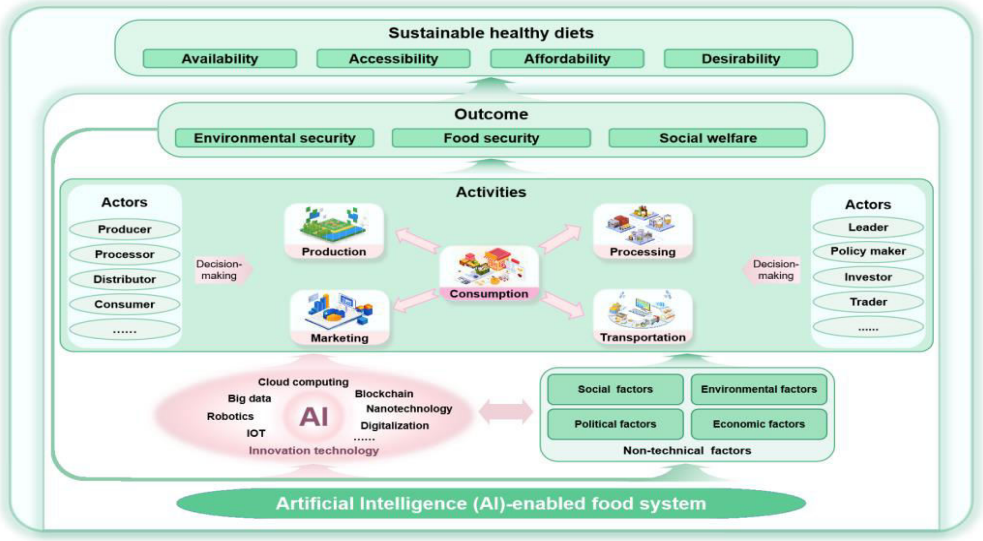

Figure 3:Machine Learning and Deep Learning Basics for Food Safety Applications

2.1. Machine Learning and Deep Learning Basics

The important concepts and terminologies related to machine learning and deep learning, forming a foundation for understanding food safety applications using artificial intelligence. Machine learning, a subfield of artificial intelligence, focuses on algorithms and software that predict outcomes based on provided data without explicit programming [4]. These algorithms learn from historical data to develop models, which can then be applied to new, unseen data to make predictions or classifications. Deep learning, on the other hand, is a subset of machine learning that employs neural networks with multiple hidden layers to learn progressively more abstract representations of data. Neural networks are computational models inspired by the human brain, consisting of interconnected nodes or artificial neurons. The learning process involves adjusting the weights of these connections based on the input data and corresponding target outputs using a training algorithm like backpropagation [12].

There are two main learning strategies in machine learning: supervised learning and unsupervised learning. In supervised learning, models are trained on a labeled dataset containing input-output pairs. The objective is to learn a mapping from inputs to outputs, enabling the model to predict outputs for new inputs. Common supervised learning algorithms include regression models, support vector machines, and neural networks. For instance, a simple linear regression model could predict the pH level of chicken meat based on its temperature at different time intervals [5]. In contrast, unsupervised learning deals with unlabeled data. The model attempts to find patterns or structures within the data without any specific target outputs. Common unsupervised learning algorithms include clustering methods and dimensionality reduction techniques. An example of a clustering algorithm is k-means, which can group food samples based on similar characteristics. For machine learning models to achieve desirable performance, it is crucial to carefully select input

features and preprocess the data before training. Feature selection involves identifying the most relevant subset of features for accurate predictions, while data preprocessing encompasses techniques such as normalization and handling missing values. The quality of input data significantly impacts model performance. A trained model can be evaluated using various metrics such as accuracy, sensitivity, and specificity. Additionally, the training dataset can be further divided to create a validation set for hyperparameter tuning and a test set for final model evaluation.

2.2. Applications of AI in Food Industry

Artificial intelligence (AI) technology has been progressively introduced to the food industry, boosting its modernization and efficiency. A variety of widely used practical applications of this technology have been explored. One salient application of AI is monitoring food quality in real-time during transport to ensure compliance with food safety standards. Adding AI technology can significantly improve the efficiency of inventory management and demand forecasting, two key aspects of the food supply chain that have been traditionally handled by human managers. For instance, the application of AI-driven predictive models to historical inventory and demand data from a fast-growing restaurant chain can optimize staffing and food orders, improving operational efficiency and profitability [1,16].

Moreover, there is a growing interest in developing AI-powered predictive analytics tools to optimize supply chain operations at food processing facilities. Food quality degradation during transport is a widely encountered problem that results in a high spoilage rate. A recent study illustrated that deep learning-based predictive models can be developed using smart sensor data to predict food quality at arrival, enabling food processors to optimally schedule transports. In addition, low-cost AI-powered sensors combined with machine learning algorithms have been implemented to detect pathogens and other contaminants in food products as well as to identify quality anomalies. Furthermore, one opportunity for implementing AI technology in the food industry is strengthening traceability from farm to fork, one of the most crucial components of food quality and safety management systems [17].

Overall, current AI applications in the food industry mainly focus on quality and safety monitoring during food processing and transport, as well as improving predictability in food supply chain management. While there remain several challenges and limitations, these impediments are potentially surmountable. As the demand for enhanced accountability and traceability in food quality and safety increases from consumers and regulatory agencies, the proactive application of AI technology will promote the food industry's compliance with safety standards and modernize food safety practices.

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3. IoT Technologies in Supply Chain Management

This section introduces Internet of Things (IoT) technologies and their significance in supply chain management. The IoT can be defined as a network of physical objects that are digitally connected to sense, monitor, and interact within a company and its supply chain [6]. By being connected to the Internet, these objects have the capability to collect and share data, and they can be anything from everyday household items to sophisticated industrial tools. Outsider devices can also be connected to this network, expanding its capabilities. IoT technologies consist of low-cost embedded systems with internet connectivity that facilitate the collection of valuable data regarding food conditions, such as temperature, humidity, gas concentration, and other relevant parameters. This data can be relayed in real-time via a centralized monitoring application, allowing concerned authorities to make timely decisions.

By attaching RFID or GPS tracking systems to food packages, it becomes possible to monitor their delivery in real-time and keep track of their estimated time of arrival. A well-designed IoT-based system can significantly enhance communication and collaboration among different stakeholders in the supply chain, such as farmers, food processors, transporters, warehouses, retailers, and so on. The IoT can also help detect irregularities and other problems in the supply chain, enabling immediate corrective actions to be taken. For instance, immediately after receiving a notification of excess temperature in a refrigerated truck, food products can be rerouted to a different location to prevent spoilage.

Logistics accounting for the movement of goods is a major part of every supply chain, and this is often a source of significant operational inefficiencies. IoT technologies can help overcome some of these problems by providing better visibility and control of food products in transit. It is possible to monitor on which truck and at what exact time a food shipment has been loaded and at which time and place it has been unloaded. If the shipment is delayed, tracking data can be used to find out the cause of the delay, whether it is due to a roadside accident, traffic congestion, or another reason. The data collected by IoT devices can also be used to analyze the past performance of the delivery trucks and drivers, and this can help improve logistics planning and scheduling. Another potential merit of IoT data analytics is the ability to predict maintenance needs of supply chain equipment, such as transportation vehicles, forklifts, and processing machinery, based on the analysis of sensor data.

This subsection reviews various IoT platforms that can facilitate monitoring the safety and quality of food products. Some platforms are sensitive to a specific data type, such as temperature, while others are more general and can accommodate a variety of data types. Moreover, the platforms differ in their features, such as whether they are cloud-based or server-based, or whether they require a subscription fee. Some platforms offer free data storage and simple data visualization tools that can be advantageous for the initial development of an IoT-based food safety monitoring system. Integration of IoT technologies with existing systems widely applied in supply chain management can substantially enhance these systems, but there are challenges regarding this

integration. These challenges and possible solutions are also discussed. Overall, in light of recent advancements in sensing, communication, and computing technologies, the impact of the IoT on enhancing food safety and quality is comprehensively reviewed from a supply chain perspective.

3.1. Introduction to IoT and Its Role in Supply Chains

The Internet of Things (IoT) technology allows interconnected devices to gather and exchange collected data, with the goal of improving supply chain effectiveness. An IoT device includes a physical component that can sense or act on the environment, enabling data collection or operation execution, as well as built-in networking capability that allows it to connect to the Internet. In recent years, food supply chains have drawn attention to the implementation of IoT devices. These systems can create a real-time picture of supply chain activities through monitoring, planning, and controlling using collected data. Monitoring temperature and humidity conditions for food products in transit and storage is critical to ensure food quality and safety. Without proper temperature control, some food products can become unsuitable for consumption within minutes. Using IoT devices to continuously track food products during transportation can improve product quality, safety, and shelf life, as well as reduce economic losses for suppliers. Currently, there is an emerging opportunity for the food supply chain to implement widely available IoT technologies to create smart supply chains that monitor and react to changing conditions in real-time [6].

In this context, existing IoT frameworks for the agricultural and food processing sectors are reviewed, along with IoT solutions for various supply chain stages. Several studies propose new IoT implementations or enhance existing solutions in these sectors. Generally, IoT devices are used to create a smart environment that gathers and reacts to data about environmental changes. A common challenge in using IoT technologies is ensuring data integration between devices from different manufacturers [13]. Security issues are also a challenge, as many IoT devices were designed for low energy consumption, limiting implementation possibilities for strong protection mechanisms. To create an effective IoT system, protocols must be standardized to ensure that devices from different manufacturers can communicate with each other. Currently, many IoT protocols exist, but most of them are proprietary, creating barriers to interoperability between devices. Another significant issue is the implementation of findings regarding the security of IoT devices. Many proposed methods require complex arrangements or solutions impossible to implement with low-cost devices. Nonetheless, IoT technology has the potential to create a competitive advantage for businesses in the food supply chain by improving product quality control, monitoring, tracking, and tracing. This introduction provides a basis for understanding the implementation of IoT technologies in the food supply chain, starting with an overview of IoT technology and its role in the supply chain.

3.2. IoT Applications in Food Industry

The Internet of Things (IoT) is a network of interrelated computing devices, mechanical and digital machines, objects, animals or people with unique identifiers that preserve and exchange data over

a network. Simple IoT devices can collect data on specific inputs, while more complex devices can sense, calculate, and act based on pre-programmed algorithms, inputs, and data collected . RFID tags and sensors are common in IoT applications in the food industry. Attaching RFID tags to food products can track them throughout the supply chain. Integrated IoT RFID temperature sensors can continuously track the temperature and humidity of food products during transportation. If the temperature falls outside the predefined threshold, the RFID tag sends an alert to the mobile application, indicating which product box to inspect. This reduces the time required to find the problematic box. Using GPS along with RFID tags further enhances control over the transportation of food products.

The IoT significantly enhances food safety by providing real-time alerts and monitoring systems. IoT devices can continuously monitor necessary parameters and alert responsible personnel when an undesired situation occurs. One application automatically updates the temperature logs for the food supply chain and compares them with the Hazard Analysis Critical Control Point (HACCP) plan. If the temperature does not meet the requirements, the system sends an email alert to concerned personnel. Another monitoring system alerts responsible employees through text messages if the temperature of a particular product box rises above the predefined threshold. Case studies on automatic monitoring systems that implement this type of IoT application are presented. Other applications are focused on smart packaging, where RFID tags with temperature sensors are attached to the food product packaging, or the use of IoT devices for automated inventory management in a warehouse. Several examples of this type of application are given. IoT applications in the food industry can enhance traceability by monitoring food products through the entire supply chain. Implementing traceability can reduce the occurrence of food fraud and adulteration and quickly identify the cause of disease outbreaks, contaminated food products, or other unwanted events in the food supply chain. Case studies where IoT technologies have been implemented to enhance food traceability are presented. Moreover, IoT applications can improve the monitoring of food quality during storage and transport and thus reduce food waste. Some food products require specific conditions to remain fresh, and monitoring the fulfillment of these conditions during storage and transport is crucial. Applications of IoT devices that monitor food quality are discussed in case studies.

Although IoT applications can significantly raise food quality and safety standards and reduce food fraud and waste, numerous challenges must be addressed. The collected data's security and privacy are significant issues. Food supply chain participants are often reluctant to share data that could give other participants an advantage over them. Another challenge is the vast number of different devices and technologies used in IoT applications. Many devices adhere to specific standards, making it impossible for different devices and systems to communicate. This paper's focus is on IoT applications in the food industry that address the above challenges. All applications are accompanied by a description of real-life implementations or proposed systems, showcasing the practical benefit of IoT technologies in the food industry. Furthermore, many IoT applications rely solely on the IoT devices used to monitor specific parameters, while integrating IoT applications with AI technologies would allow for predictive aspects. For example, IoT

temperature sensors can continuously monitor the food product temperature during transportation, and if the temperature anomaly is detected, it may indicate that a food product has gone bad. By integrating with AI technologies, models could be developed to determine the probability of food products going bad based on the temperature anomaly and other input parameters, leading to more informed decision-making. An overview of AI technologies used in the food industry is provided.

4. Integration of AI and IoT in Food Supply Chains

Integration of AI and IoT technologies for food supply chains has become an important topic in both industry and academia. Advances in artificial intelligence (AI) provide powerful technology for the analysis of data and modeling of complexity. The Internet of things (IoT) provides technology for data collection. The synthesis of AI and IoT enhances decision-making and responsiveness of the food supply chains from the farm to consumer. This topic summarizes the trends, benefits, challenges, and examples of the integration of AI and IoT technologies in the food supply chains. Food supply chain stakeholders can benefit from the information in this chapter to promote collaboration in research, knowledge transfer, and system implementation [6,11].

Artificial intelligence (AI) and the IoT have emerged as crucial technologies for the competitiveness of industries, including food production and processing [9]. AI can improve productivity, effectiveness, and flexibility by enhancing decision-making and automating processes. Data collected and shared through networks are becoming a foundation for AI applications. IoT technology has developed various low-cost sensor systems for data collection and networking. The adoption of these technologies in food supply chains can promote food quality and safety. However, the deployment of AI and IoT technologies poses challenges, including cost, lack of technical expertise, and concern over data security. These issues must be addressed by researchers and industry for wider adoption.

4.1. Benefits and Challenges of Integration

The integration of artificial intelligence (AI) and the Internet of Things (IoT) in food supply chains brings a range of benefits and challenges. On the positive side, their combination enhances automation and efficiency, leading to cost savings, reduced food wastage, and improved overall food quality. AI-driven analytics can utilize IoT-generated data to make better operational decisions, optimizing logistics and production planning. Real-time data analysis allows businesses to monitor operations continuously and respond promptly to issues, facilitating better tracking of food quality throughout the supply chain. Such data analytics can provide predictive insights, helping managers proactively address potential food quality problems before they arise [6].

The integration of AI and IoT technologies can significantly improve food safety throughout the supply chain. By installing IoT sensors on food packages, parameters like temperature and humidity can be monitored during transportation. Analytics on this data can identify links between

food safety hazards and changes in monitoring parameters, allowing businesses to take preventive actions against food safety risks. Nevertheless, despite the numerous advantages of combining AI and IoT, several challenges need to be critically assessed [18]. The high upfront costs associated with the implementation of IoT and AI technologies can be a deterrent to many food businesses, particularly small and medium-sized enterprises. Additionally, the effective use of these technologies requires a certain level of technical expertise and experience, which many companies currently lack [7]. There are also concerns regarding data security and privacy, which are crucial in establishing trust between different stakeholders in the food supply chain. The food industry's readiness to adopt these combined technologies is also analyzed, as many companies still rely on less advanced technologies.

4.2. Case Studies and Success Stories

Several successful examples of integrating AI and IoT into food supply chains are presented in this section. Each case study presents a unique application and highlights the main results and lessons learned. The studied initiatives encompass a variety of applications and have led to improved efficiency, reduced spoilage, and more effective safety measures. The examples cover various sectors, including agriculture, processing, distribution, and retail. It is emphasized that collaboration among different stakeholders is crucial for success. On the other hand, when a single stakeholder implements their solution, it often requires more time to prove its value. The importance of constant monitoring, assessment, and adjustment of these integrations is also underlined. Several challenges are described, along with strategies for addressing them [1].

Case Study/Success Story	Application/Outcome	Key Technologies	Impact/Benefits
AI for Shelf Life Prediction in Dairy Products	Predictive models for assessing remaining shelf life of yogurt based on temperature history	Machine Learning Regression Algorithms	Reduced spoilage, better supply chain planning, enhanced quality assurance
IoT-Based Monitoring of Perishables	Real-time temperature and humidity monitoring during transportation of fresh produce	IoT Sensors, Cloud-Based Gateway	Improved product quality, reduced waste, ensured compliance with safety standards
Blockchain Integration in Supply Chains	Blockchain used for traceability and secure tracking of IoT device data and food transfers	Blockchain, IoT	Enhanced transparency, secure data sharing, and improved trust among stakeholders
Predictive Analytics in Risk Management	AI models analyzing past incidents to predict and prevent foodborne outbreaks	Deep Learning, Predictive Analytics	Minimized outbreak risks, faster response times, and proactive safety measures

AI and Computer Vision in Quality Control	Automated defect detection in processed food products during manufacturing	Computer Vision, AI Algorithms	Reduced reliance on human inspection, consistent quality control, minimized defects
IoT in Warehouse Inventory Management	Smart inventory systems for monitoring stock levels and ensuring optimal storage conditions	RFID Tags, IoT Devices	Reduced overstocking, minimized losses due to spoilage, and optimized storage conditions
Drone-Based Monitoring of Agricultural Fields	Drones equipped with IoT sensors for assessing field conditions like pest infestations and water management	Drones, IoT Sensors	Reduced pre-harvest risks, optimized resource use, and better crop quality
AI-Driven Demand Forecasting	Historical sales and demand data analyzed to optimize food production and reduce waste in restaurant chains	Machine Learning, Predictive Analytics	Improved operational efficiency, reduced food waste, and better demand-supply balance

Table 1 :Case Studies and Success Stories of AI-Driven Predictive Models and IoT-Based Solutions in Enhancing Food Quality and Safety [1,4,7,15,18,19]

In total, seven various examples of technology integration in food supply chains are studied. They were carefully selected to cover different parts of the food chain, including agriculture, processing, distribution, and retail. The examples comprise diverse approaches, from a fully automated IoT deployment designed and implemented by a single food producer to several collaborative projects involving public institutions, universities, and multiple food chain stakeholders. This selection aims to illustrate the wide applicability of the presented technologies and approaches, emphasizing that they can be tailored to different circumstances and specifications. However, it is noted that other solutions could still be beneficial but were not selected for description due to space constraints [2].

5. Future Directions and Conclusion

There is a need for ongoing innovation in the development of predictive models, IoT solutions, and applications that can be used by stakeholders to easily implement and benefit from these technologies in order to enhance food quality and safety during production and throughout the supply chain. The current and future potential of AI-driven solutions and IoT technologies to evolve and provide significant contributions to the food supply chains is presented. Several proof-of-concept implementations and commercial products that provide enhancement to food supply chains via new technologies are showcased. It is anticipated that many of these developments will significantly impact the future of food supply chains; however, several technology and standards

prerequisites still need to be addressed before becoming commonplace [1]. Industry 5.0 principles and ethos should be considered when developing new technologies and solutions for the food supply chains to enhance food quality and safety [10]. This will ensure that good and safe food is available to all and that food supply chains evolve towards resilience, inclusiveness, sustainability, and productivity. Potential topics for future research were identified, such as the mechanism for free access to big data collected by IoT devices, models, and AI solutions in order to drive the innovation across the whole food supply chain rather than being locked-in at the industry leaders; bringing the AI-driven solutions out of laboratory conditions to become usable by small and medium enterprises; ensuring compliance of new technologies with the existing food safety regulations; and ethical principles of technology adoption in food systems from the production to consumption phase. Finally, as with any technology, there is a need to educate all stakeholders from producers to consumers on how to properly use and benefit from these technologies. Many technology solutions have inherent and significant advantages over the traditional ones; however, when poorly or misused, these advantages can be diminished and even reversed. Therefore, it is important to ensure that adequate training is provided to all stakeholders on how to best use the technologies that will be adopted. A proactive approach should be taken to ensure that the AI-driven and IoT technologies will be properly used to continually enhance food quality and safety in the good and safe food supply chains [2].

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