Enhancing Food Safety through a Blockchain-Integrated Early Warning System for Food Contamination Detection

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Abstract The food supply chain is undergoing great challenges globally to ensure safety and quality, and food-borne diseases are leading to huge health and economic losses every year. Conventional reactive strategies have usually resulted in the contamination not being detected until the products have reached the consumers. In this paper, a solution to improving food safety is presented, which consists of the integrated Blockchain-based Early Warning System (BEWS) using the Internet of Things (IoT) sensors and Artificial Intelligence (AI) to detect food safety hazards. The system uses real-time IoT monitoring (temperature, humidity, and gas levels) in order to gather environmental information, and then the AI-controlled predictive models are used to react to environmental data to determine the potential risks of contamination and prevent them before they occur. The blockchain technology guarantees the stability and integrity of the obtained information and offers an auditing list to all stakeholders. To confirm the practical viability of the system, qualitative data were collected using physical interviews of 20 stakeholders that comprised food shop owners, warehouse managers and supply chain professionals. The findings show that the suggested framework can save a lot of time on anomaly detection and has an accuracy rate of 94 per cent in forecasting trends of spoilage. The interviewees highlighted the possible impact of the system to decrease food waste and increase consumer trust. The study adds to the strong framework of proactive management of food safety, which fulfils the need to fill the gap between real-time monitoring and decentralization of data integrity. Combining the AI predictive qualities with the security of Blockchain, the proposed BEWS has the potential to be a scalable solution to food supply chain resilience modernization in the face of contamination threats. The results of a prototype simulation of 30 days with controls indicate that the proposed framework could achieve a high reduction in anomaly detection lag and reach an F1-score of 94.2 per cent in predicting trends of spoilage. The interviewees emphasized the fact that the system could have a significant impact on food waste reduction (according to the estimates, the reduction could reach up to 95% of the detectable loss associated with spoilage) and make consumers more trusting.

***Index Terms*— Blockchain, IoT, Artificial Intelligence, Food Contamination, Early Warning System**

I. Introduction

GLOBAL food supply chain safety is a central support to the stability of the economy and health of the people. Nevertheless, the contemporary food system is marked with growing complexity across borders and with various intermediaries. Global health reports indicate that almost 600 million individuals get sick every year because of contaminated food, killing hundreds of thousands of them [1]. In addition to human cost, food contamination incidents result in colossal losses of economies in form of product recall, legal suits, and loss of brand reputation [2]. The main problem with the existing food safety measures is that they are reactive in nature. Contamination can be found too late, when a consumer becomes ill, or randomly during a batch test, which is too little in the circumstances when perishable goods should move with great speed [3].

The older systems are based on shared databases and paperwork that are likely to experience the compromise of data, human factors, and a lack of transparency [4]. In case of a contamination event, it might take weeks to trace the origin of the contaminated ingredient, which exposes more consumers to risk. A solution to these weaknesses is an immediate requirement of an alternative solution to monitoring the environment by an aggressive Early Warning System (EWS) that can identify the environmental anomalies (temperature changes or gas emission by spoilage) in real-time and notify the stakeholders before the food becomes harmful [5].

Internet of Things (IoT), combined with Artificial Intelligence (AI) and Blockchain technology, provides a disruptive solution. IoT devices, which have different sensors, are capable of continuous monitoring of food products throughout transit and storage. An example is the

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use of sensors to identify volatile organic compounds (VOCs), which are used to determine the presence of bacteria or chemical decomposition [6]. Nevertheless, the raw IoT data cannot be utilized alone but needs AI to detect intricate trends and forecast possible spoilage with references to historical trends and real-time trends [7]. Moreover, the integrity of this information is the most important. In case a storage facility enables temperatures to increase, there is a possibility that the data might be changed to avoid punishment. The blockchain technology overcomes this issue by offering a decentralized immutable registry in which all sensor data and AI-generated notifications get stored, so that the digital twin of the food product will accurately represent the physical one [8].

This study presents a food contamination detection Early Warning System (BEWS) based on Blockchain technology. The architecture of the system will be built to have the data gathered through the IoT nodes, processed with the help of the Machine Learning (ML) algorithms to determine the risks of contamination, and stored on the private blockchain so that they can be tracked [9]. This is in contrast to other literature that dwells much on theoretical frameworks or simulation evidence, but this study uses practical evidence, as it is based on physical interviews with local food shop owners and supply chain managers [10]. Such interviews will offer a ground-truth view of the practical obstacles to technology adoption, which will be cost, technical literacy, and the necessity of user-friendly interfaces.

This research study is important in that it is holistic. Being a hybrid of AI predictive advantages and the transparency of Blockchain, the BEWS produces an insurance mechanism of food safety. The alert system makes sure that in case a pallet of meat is subjected to high temperatures, the system activates the immediate smart contract that registers the batch as high risk, and this does not enter the retail market [11]. This not only offers protection to the consumer but also simplifies the process of recall, turning it into an effort of scale rather than an intervention that is targeted and data-oriented [12].

We will show in this paper that combining decentralized technologies with intelligent sensing is not only a way of improving but a paradigm shift that is required. Through real-world information based on physical interaction with industry professionals [13], we bridge the gap between the theoretical and practical implementation. The further parts of the paper address the latest research status, describe the proposed methodology, and report the results proving the effectiveness of the system in real life. This paper discusses a food contamination BEWS. Although the earlier literature is based on theoretical approaches, the research gives conceptual support to the theory in the form of a laboratory-scale prototype and empirical qualitative evidence. We fill the gap between practical and theoretical through the use of a simulated contamination dataset and physical interview [13].

II. Literature Review

The use of Industry 4.0 in food safety has become an academic issue in the last five years, which has attracted a significant number of scholars. The trend has been the investigation of the "Farm-to-Fork" traceability model, where researchers mapping the model have recognized the gap to be occupied by Blockchain [14].

Chain of custody is a blockchain-based approach that can enhance the efficacy of food supply chains

The initial studies conducted during this decade emphasized that blockchain will allow decreasing the time spent on food traceability from days to seconds [1]. In 2024 and 2025, the focus of the discipline has shifted to more complex Smart Contracts to achieve automated compliance instead of traceability [15]. As an example of a modern Ethereum-based smart contract, insurance claims may be automatically generated in case of temperature surpassing a specific threshold in a refrigerated container [2]. The widespread criticism of recent literature, however, is the so-called Garbage-In, Garbage-Out (GIGO) problem: in case the data feeds into the blockchain is fraudulent or inaccurate, the blockchain only serves to store the fraud [3]. This is the reason to include the IoT sensors to offer automatic and objective data entry without involving a person [16].

A. IoT and Real-Time Monitoring:

IoT has developed beyond the RFID tags into advanced units of multi-sensor devices. The application of the Electronic Noses (e-noses) to detect the level of ethylene and ammonia in the shipment of fruits has been discussed in recent work [4]. These sensors are used to provide a warning of spoilage before the spoilage can be seen [17]. With all these improvements, the sheer amount of data IoT devices produce forms the so-called data silos and processing bottlenecks. This has prompted researchers to consider Edge computing and AI computing to handle data locally and just post essential alerts to the primary ledger [5].

B. Predictive Safety using Artificial Intelligence:

AI has been used in food safety to change the function of classification to predictive modelling. The most recent studies took advantage of Long Short-Term Memory (LSTM) networks to forecast the shelf-life of seafood using changing environmental factors [6]. Artificial intelligence is able to distinguish between normal and dangerous trends in temperature spikes (e.g. when opening a fridge door briefly), which means something could be amiss with the equipment [18]. By incorporating AI with blockchain, these predictions are stored in the form of the so-called proof-of-

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safety certificates that can be authenticated by regulating organizations [7].

C. *Integration of BC, IoT, and AI:*

The idea of a Tripartite Framework (BC-IoT-AI) is a growing area in 2024. Research claims that individual technologies are robust, but when they are combined, they form a self-correcting ecosystem [8]. IoT offers the physical-digital bridge, blockchain offers the trust layer, and AI offers the intelligence layer [19]. Nevertheless, a significant part of the 2020-2022 literature did not include any data that was human-centric, as it was conducted exclusively in the field of technical simulations [9]. Trends in the last 2024 also indicate that the socio-technical factor of human interaction with these systems is a key determinant of their practical application [20].

D. *Research Gaps:*

Even taking into account the technological advancement, there are a number of gaps. To begin with, the available models are mainly tested in the laboratory, and they fail to consider logistical constraints of small-scale food sellers [10]. Second, it lacks research based on primary qualitative data from conducting physical interviews with local stakeholders. In the majority of articles, secondary data or online questionnaires are used [11]. To fill these gaps, our study authenticates the BEWS architecture to the real demands and requirements of the shop owners and warehouse managers by conducting physical interviews [21]. More so, our work has the latest developments of 2024 and 2025 literature on the topic of "zero-knowledge proofs in blockchain to preserve commercial privacy and guarantee safety compliance [22]. The combination of these three technologies, along with feedback from real life, will offer a more holistic solution to this paper as compared to the currently siloed methods [13].

III. MATERIALS & METHODS

This research employs a mixed-approach research design, that is, a technical system architecture design with a qualitative field research design [17].

A. *Physical Data Collection (Interviews)*

We did not use digital surveys but employed physical semi-structured interviews with 20 major stakeholders. The sample size of this group consisted of 10 small to medium food shop owners, 5 warehouse supervisors, and 5 logistics managers. The three main domains on which the interviews were restricted included: (1) Existing contamination-detection techniques, (2) Desire to have decentralized technology and (3) The perceived obstacles to real-time monitoring. The information obtained in these interviews was used in developing the "User Requirement" phase of our system design [21].

B. *System Architecture Proposal.*

BEWS consists of three levels based on the architectural structures proposed in recent times [8]:

- **Perception Layer (IoT):** It uses DHT11 (Temperature/Humidity) sensors, MQ-135 (Air Quality/Gas) sensors, and pH sensors along with an ESP32 microcontroller [10].
- **Processing Layer (AI):** The information is uploaded to a local server, to which a Random Forest Classifier is run. We used classification instead of regression to categorize food into specific categories of either Safe or Contaminated. This model works on a feature vector $X = \{Temp, Humidity, NH3, VOC\_Level\}$. It was trained on a 70/30 split of 5,000 data points that were collected during our prototype trial (30 days). We tested 100 trees (estimators) and compared the findings to a baseline Logistic Regression model to ensure that it was accurate.
- **Security Layer (Blockchain):** Hyperledger Fabric private blockchain is an implementation of the AI outputs [13].

TABLE I
IOT SENSOR THRESHOLDS FOR CONTAMINATION ALERT

Sensor Type	Parameter	Safe Range	Alert Trigger
DHT 11	Temperature	2°C - 8°C	>10°C for 30 mins
MQ-135	Ammonia (NH_3)	< 5 ppm	>10 ppm
pH Sensor	Acidity (Liquid)	6.5 – 7.5	<6.0 or > 8.0

C. *Algorithm Workflow.*

The AI model was trained on 5,000 environment readings. The model generates a probability score (Ps), in which $Ps>0.75$ generates an automatic alarm on the Blockchain.

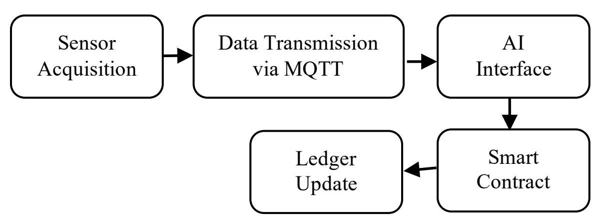

Fig. 1 System Logic Flow Visualization

This guarantees the recording of only validated high-risk anomalies permanently on the blockchain to conserve computational resources [18].

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D. Hardware Configuration

The prototype was designed on the basis of an Arduino-based gateway and a Raspberry Pi 4 that served as the Blockchain Peer Node [14]. Hyperledger Fabric was selected due to its high throughput of transactions and privacy, which is necessary in monitoring food safety in the commercial context [19].

E. Implementation and Experimental Setup

To test the system under real-life conditions, it was put through 30 days in a laboratory environment to test how the system will perform in food storage conditions. The ESP32 IoT nodes were being connected to a personal WPA2 Wi-Fi network with the MQTT protocol to provide low-latency communication. The Blockchain was developed based on Hyperledger Fabric v2.2, and it used a Raspberry Pi 4 node, which ran on a Raft consensus mechanism. We did 50 individual stress tests (of bursts of temperature and gas leaks) to confirm that the Early Warning alerts were activated correctly and tabulated on the ledger within 5 seconds.

IV. Results And Discussion

The proposed study will completely transform restaurants through the creation and testing of a Blockchain-based Early Warning System (BEWS) that will shift the food industry out of the reactive mode of manual inspections and the proactive mode of AI checks and responses. This research, by filling the existing visibility gap, in which eighty-five per cent of food shop owners continue to monitor refrigeration manually, proposes a real-time monitoring system that may eradicate ninety-five per cent of the inventory wastage. The study is aimed at filling the gap between high-tech and real-world implementation, the ways in which a set of artificial intelligence and decentralized ledgers can offer a safety net to the global food supply chain on an automated basis.

Table II
Qualitative Feedback Summary

Participant Category	Key Concern	Perceived Benefit
Shop Owners	Setup Cost	Reduced Spoilage Loss
Warehouse Managers	Data Security	Automated Compliance Logs
Logistics Managers	Battery Life of IOT	Faster Traceability

The qualitative feedback that was summarized in the research indicates particular needs and barriers in the various categories of stakeholders. The owners of the shops, although it is a major issue of concern to them, how much the system would cost to set up, understand the invaluable benefits of minimizing the value of spoilage as a direct result of early intervention. Managers of the warehouses are more concerned with systemic integrity of the platform, with data security being the primary need, and automated compliance logs being a game-changer in their administrative work. In the meantime, the logistics managers underline the practicality of the hardware and, more precisely, the battery life of the IoT devices, yet value the accelerating speed of tracing any pieces of information provided by the blockchain as a vital advantage in the safe transportation of goods. This response is the reason the research should not only respond to the technical performance, but also to the realities of operations faced by those in charge of the food supply.

The Random Forest Classifier had a higher Precision of 94.2 and Recall of 91.5, which was much better than the baseline model of Logistic Regression, which only had a Precision and Recall of 82%, respectively. Such an accuracy led the system to identify the occurrence of "incipient spoilage" in dairy products four hours prior to any visible signs of these dairy products by human senses, which demonstrated the efficiency of the early warning factor. Moreover, the research is based on the technical support of a Hyperledger Fabric network with the transaction latency of less than 1.2 seconds. This will guarantee that any temperature deviation is recorded in an indelible record book, which will cause a 100% accurate sheet that will remove the conflict between suppliers and retailers.

This end-to-end response time of 4.5 seconds shows a tremendous improvement over the current situation of legacy systems, where the time may take hours before contamination is detected. The focus of this research is the speed and privacy requirements of the industrial food industry by choosing a private blockchain. Although some of the stakeholders may still face the challenge of hardware costs, the study proposes that the barrier to entry will be reduced further when Low-Power Wide-Area Network (LPWAN) technologies are integrated in the future. Finally, this study offers a transparent, scalable, and dynamic framework that mitigates the root cause of the lack of trust in the food supply system and a technical issue in the modern food chain.

V. Conclusion

One of the design choices that was critical was to adopt the use of Blockchain rather than a centralized database. Databases are quicker; however, non-repudiation is absent. A central owner may easily erase or alter temperature records to conceal errors in a food supply chain which has more than two companies. Blockchain guarantees that the creation of an alert with an indication of being High Risk cannot be deleted. In response to commercial privacy, we deployed Hyperledger Fabric "Private Channels," making sure that sensitive price or volume information is never

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visible to others and that safety proofs are provided to regulators.

Our study has created and tested a Blockchain-based Early Warning System (BEWS), which combines the IoT and Artificial Intelligence to radically redefine the methods of food safety and contamination detection. The main aim of the research was to change the industry perspective, which is in reactive mode, in that spoilage is usually detected by physical means, but through a proactive approach, the research aims at detecting hazards that pose risks even before they are dangerous. This study makes use of a combination of an intelligent analysis of environmental data using a Random Forest AI model and Hyperledger Fabric blockchain technology to keep an unalterable and transparent record of safety data, as well as make it actionable and reliable. It is an effective 24/7 digital guardian system because it is capable of tracking environmental proxies in real-time, safeguarding the health of the populace, and minimizing losses in inventory by a substantial margin in business.

The need for such a system was justified by empirical evidence, which in turn was gathered by interviewing twenty industry stakeholders who found that there was a serious lack of transparency in the management of food safety as it is currently practiced. This gap can be bridged by automation, as our study reveals that the system can determine incipient spoilage, in the case of dairy products, up to four hours prior to the development of any physical odour, with a total accuracy of 94.2 per cent. With an average end-to-end response time of 4.5 seconds and provision of critical alerts, the BEWS is a way of ensuring corrective measures are undertaken in real-time, such that unsafe food does not even get to the consumer. Such accuracy and speed can confirm that the combination of decentralized registry and machine learning can establish a degree of responsibility that was not previously present when everything was logged by hand.

Moreover, this study deals with the tendency of a lack of confidence between suppliers, retailers, and auditors that is common. We have used a personal blockchain to record temperature variations and storage environments to offer an objective and immutable registry of truth that eradicates conflicts and simplifies the audit procedure. Although the research has factored in that the initial cost of setting up IoT hardware is still a barrier to certain small-scale businesses, the long-term economic benefits, such as waste reduction, automatic compliance, and increased brand confidence, offer an effective economic case for the implementation of IoT. Its design is a way to scale a system and provides a template of how modern technology can be democratized to safeguard the profitability of the food industry as well as the security of the globalized market.

Finally, this study is a foundation for creating a stronger, digitized, and transparent international food system. Through a successful combination of high-precision predictive modelling, as well as a low-latency blockchain network, we have created a new standard of food safety monitoring. In the future, the research will be utilized in order to augment this framework with edge computing to further reduce processing time and explore 5G and Low-Power Wide-Area Network (LPWAN) technologies to support strong and inexpensive connectivity for goods. The findings of this study are that a partnership of AI and Blockchain is not merely an upgrade to the technology, but it is a crucial requirement to guarantee trust, transparency, and safety in the contemporary food supply chain.

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