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Enhancing food quality and traceability through the integration of biosensors and blockchain technology

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Abstract

Objective

Food contamination and food waste have contributed significantly to the rising incidence of foodborne illnesses and food scarcity globally. There is a pressing necessity to create a more intelligent food traceability system. Recent breakthroughs in biosensor (BS) technology have resulted in the development of user-friendly, fast, specific, highly sensitive, and affordable BSs. These improvements hold significant potential in addressing the urgent need for on-site and prompt detection and treatment of food security and quality control issues, commonly referred to as point-of-care technologies. Blockchain (BC) offers an unchangeable and easily visible record that brings benefits in the traceability of fresh food quality and the real-time monitoring of it.

Results

This paper explores the correlation between BC, traceability, and real-time food quality monitoring. It highlights the latest technological advancements in food tracing and continuous surveillance that can offer valuable data for BC implementation. The discussion focuses on using BSs in farming at the pre-harvest phase to identify and manage plant diseases or stresses at an early phase.

Conclusions

This article focuses on the recent progress in BSs within the Food Supply Chain (FSC), specifically in the post-harvest phase. It highlights the advancements in detecting various types of food pollutants and the development of intelligent food packaging.

Keywords: Biosensors, blockchain, food quality, traceability

Paper Type: Review Paper.

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Introduction

Fresh food refers to healthy, sanitary, unprocessed meals, typically fruits, vegetables, raw meat, and aquatic goods (Chen et al. 2020). Unlike other consumer items, fresh food contains a significant amount of water and is susceptible to decay, leading to a limited period in which it is stored. Being a consumable item, ensuring safety is of utmost importance. To cater to the diverse preferences of customers, it is necessary to offer a wide range of fresh food options. The outlook for fresh food is less promising than anticipated. Firstly, the perishability of these food products requires their storage and transportation to meet specific requirements. Secondly, the lack of supply chain systems hinders the exchange and analysis of food information, making it challenging to promptly identify issues throughout the Food Supply Chain (FSC) (Rizou et al. 2020). It is imperative to precisely track and consistently monitor the quality of perishable food items. Blockchain tracks every stage in the food supply chain via a decentralized, unaltered record. From sourcing to distribution, it saves crucial data points for transparency, security, and real-time product origins and handling.

Intelligent food traceability is a very effective solution for addressing the worldwide issues associated with food omics (Islam & Cullen 2021). Food omics refers to the comprehensive analysis of food, including its nutritional content, quality, genuineness, safety, and stability (Dessy et al. 2023). Biosensors (BS) are reusable and can replace traditional analytical methods by providing speedy, precise, dependable, and multifaceted assessments (Balkir et al. 2021). Extensive research has been conducted on developing BSs for food security and evaluation. These breakthroughs include creating portable devices that can identify foodborne illness pathogens in contaminated foods (Ozyılmaz et al. 2022). BSs operate on the fundamental premise of combining a bioreceptor, a natural recognition component, with a transducer, a sensing component. This combination produces a quantifiable signal directly related to the quantity of analytes (Surendar et al. 2024). Various BSs have been identified and categorized by the type of bioreceptor they employ (such as enzymes, antibodies, microorganisms, etc.). However, their importance often lies in their ability to interact with analytes. The electrolytic BS is typically the most prevalent form based on its transducer, with additional types, including visible and mass-sensitive BSs (Ozgür et al. 2022). While several reviews are available on current advancements in BSs for food systems, finding one that specifically focuses on using BSs throughout the entire complex BC must be completed. Moreover, data generation in agriculture and biotechnology has greatly increased in recent years due to the very rapid development of high-performance technologies (Mohammadabadi et al. 2024). These data are obtained from studying products, foods, and biological molecules, such as metabolites, proteins, RNA, and DNA, to understand the role of these products and molecules in determining the structure, function, and dynamics of living systems (Pour Hamidi et al. 2017). Functional genomics is a field of research that aims to characterize the function and interaction of all the major components (DNA, RNA, proteins, and metabolites, along with their modifications) that contribute to the set of observable characteristics of a cell or individual (i.e., phenotype). Artificial neural networks have been proposed to alleviate this limitation of traditional regression methods and can be used to handle nonlinear and complex data, even when the data is imprecise and noisy (Pour Hamidi et al. 2017). Agricultural data can be too large and complex to handle through visual analysis or statistical correlations. This has encouraged the use of machine intelligence or artificial intelligence (Ghotbaldini et al. 2019). Thus, this review aims to integrate prior research on BSs in food safety and evaluation, from pre-harvest to post-harvest stages.

To guarantee consumers' access to information regarding the various stages of producing, gathering, handling, and delivering fresh food, as well as to strengthen oversight of the fresh BC and the growth of fresh food companies, the fresh food quality and security traceability and transportation data management structure are implemented across the entire manufacturing, preparation, packaging, transportation, and retailing process. The system encompasses manufacturing, processing, warehouses, shipping, and retailing, all centrally managed through an information processing system to enable efficient operation and management (Nair et al. 2019).

The government primarily oversees the conventional food traceability structure, which has a hierarchical structure starting with the central traceability platform, then extending to the province traceability platform, and finally to the local traceability platforms (Yu et al. 2022). The local traceability management system supervises each sub-system of the circulation nodes. The government's traceability administration system often utilizes wired secure network distribution, but the traceability sub-system that gathers data commonly relies on wireless networks and Internet communication. The primary goal is to trace the origins of fresh food, its location, traceability of accountability, government assistance, manufacturing self-regulation, and consumer oversight (Qian et al. 2020). It aims to establish unified collection metrics, coding regulations, dissemination forms, and interface requirements. This traceability system encounters substantial investment requirements, sluggish outcomes, challenging maintenance, and onerous burdens and needs a market-driven development characteristic.

Studies on BSs have garnered researchers' interest, aligning with intelligent food traceability advancements. The advancement of BSs has effectively overcome the limitations of several portable traceability systems (Bankole et al. 2022). BSs are well recognized in the BC for fulfilling the crucial need for on-site and fast detection and management of food quality issues. This is because BSs allow for the quick and accurate detection of certain substances while being sensitive and cost-effective. One of the main advantages of this technology is its user-friendly nature since it does not need complex or costly processing of samples. This aspect has made it suitable for Point-Of-Care (POC) applications (Xing et al. 2022). The focus of POC in the BC often centers around the issues of nutrient surveillance, security and integrity of food, and management of the food manufacturing ecosystem.

The current benchmark for modern food traceability systems integrates Big Data (BD) (Jin et al. 2020) blockchain (BC) (Burgess et al. 2022). Internet of Things (IoT) (Bobir et al. 2024; Ben-Daya et al. 2020), and Artificial Intelligence (AI) technologies (Sahni et al. 2021; Mumtaj Begum 2022). In the age of mobile IoT, every product is equipped with a unique identification number, enabling a single code for every product and facilitating real-time tracking and input on the BC. The newly implemented traceability mechanism ensures the brand's integrity while upholding customers' rights. Unlike conventional networks, BC offers two distinct benefits: decentralization and information immutability. The information it provides is reliable and authentic, resistant to modification, and capable of resolving the problem of mutual distrust.

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Customers can obtain products directly or indirectly via the appropriate technology, enabling them to act as media and convey the unique narrative of each brand. New technologies like the Internet of Things (IoT) and blockchain make it possible to monitor the status and condition of food in real time.

Blockchain: This system is capable of recording and tracking data at every stage of the food supply chain, from production to consumption. Due to blockchain's immutability and transparency, customers can see where their products have come from. In the event that the shipment goes missing or becomes contaminated, this might be useful in determining the last known handlers, locations, and times of documentation.

Internet of Things: At every checkout counter, Internet of Things (IoT) sensors may monitor how fresh the food is and transmit that information to the cloud and blockchain. This may be useful for managing stores in real-time and increasing transparency.

Blockchain and BSs-based food quality and traceability

BC has a substantial influence on the FSC of fresh food. The system is now divided into many levels: the consumer level, representation level, corporation and application level, consensus and network level, data level, data gathering level, and operation level (Figure 1). Irrespective of the layer, ensuring the traceability, security, and quality of fresh food are of utmost importance. Therefore, developing novel technology capable of providing rapid real-time data on perishable food items is imperative. BCs have benefitted from fresh innovations, which provide more reliable data support and comment on outcomes. Emerging technologies are classified into two groups depending on their capacity to track the origin of food and check its quality in real-time. There are four main components to a supply chain (SC): manufacturers, wholesalers, retailers, and transportation. Through a network of SC partners, milk products are distributed from producers to consumers. At first, the producer makes dairy products and packages them in a unique container with the passive RFID tag. Before shipment, the RFID gate reads the tagged items as they enter the cold storage and records their Electronic Product Code (EPC) and unique identifier (UID). The host computer receives this data and uses it to create product details such as business steps (product status), event time, business location, and EPC. The EPC Information Service (EPCIS) server side receives all of these facts thereafter. The carrier hands over the goods to the wholesaler once they are prepared to be moved. The manufacturer and distributor units have cold storage facilities with fixed RFID readers, whereas the transporter uses a handheld device. The RFID reader scans the tagged items at the distributor before storage and, lastly, another transporter delivers them to the user. The traceability system keeps track of the tagged items whenever they are transported. To find out which way the tag is facing, the manufacturer and seller use a tag direction module. The tag direction module uses an ML model to determine the direction of movement, such as entering or leaving the facility, making it easier to identify items that have been dispatched or received. In addition, manufacturers, wholesalers, and carriers all make use of humidity and temperature sensors that are based on the Internet of Things. We then send the data collected by the IoT sensors and the RFID readers to the web service so they may be stored in our database. In this way, product safety and quality can be guaranteed throughout the SC, and items can be traced in real-time. The food traceability system's block diagram is shown in Figure 1.

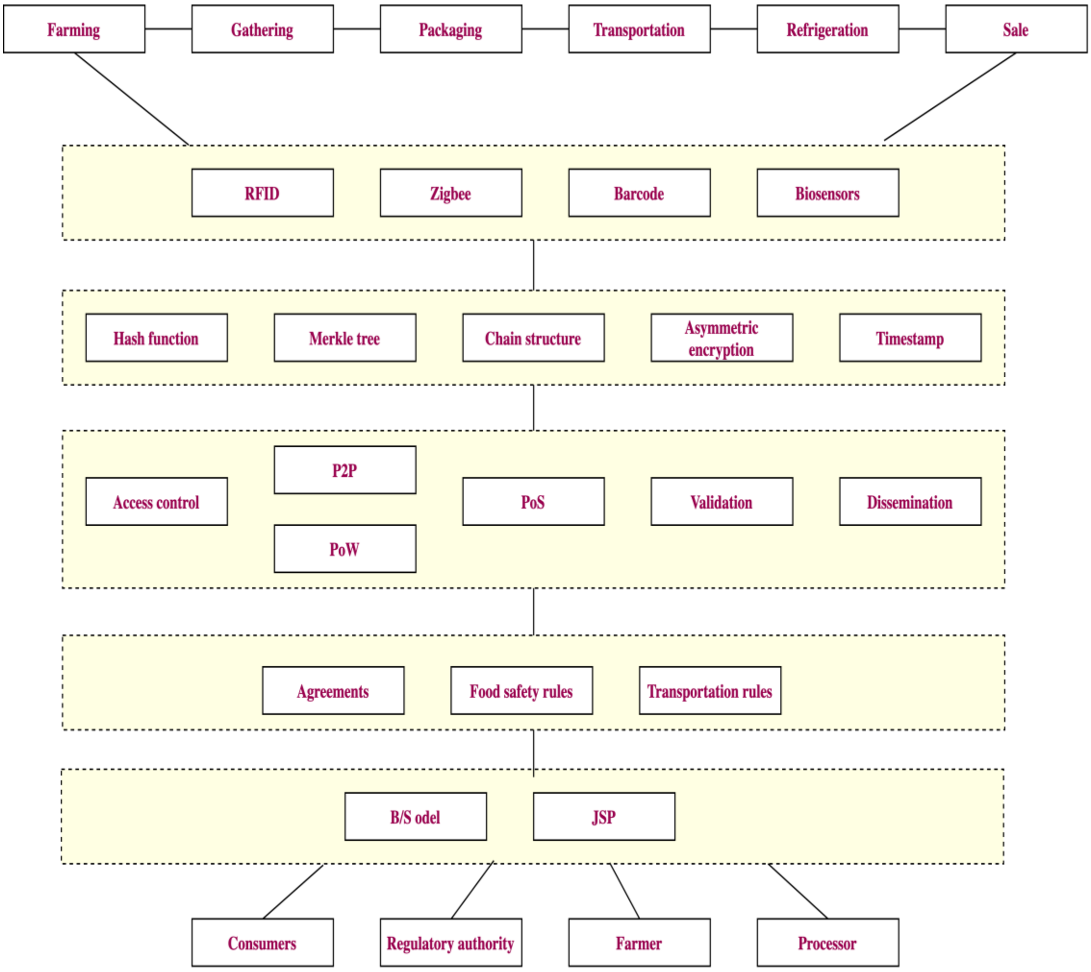

Figure 1. BC and BSs-based Food Quality and Traceability Model

Collecting data throughout the BC is essential for the proper functioning of the BC, as it will contribute a significant volume of information to the BC's data level. The immutable feature of BC is crucial for continuously tracking food goods. The constant monitoring of fresh food is essential for assuring its quality. Key factors that impact the quality and safety of food items often encompass humidity, temperatures during storage, and quality indications. Biogenic amines, volatile organic chemicals, volatile elemental nitrogen, bacterial matters, and decomposition products are dependable markers of food freshness, as a growing body of research demonstrates. Managers can detect changes in the storage setting and promptly make any required adjustments or rectifications by continuously monitoring quality parameters. Online analysis facilitates tracking product quality parameters across the whole FSC. Sensors and intelligent recognition are the prevailing technology for real-time food monitoring.

BSs in food safety and security

The rapid growth of the population has led to a higher demand for food, which has necessitated the need to address the food security dilemma and find a solution via the evolution of the food industry. To ensure financial, environmental, and social sustainability, resilience, and efficiency, the food system should implement a comprehensive strategy encompassing all aspects of the BC, from manufacturing to consumption. BSs have several uses in ensuring food safety and security. These include identifying foodborne microorganisms, poisons, veterinary medications, pesticides, and other chemical substances such as food allergens and toxic metals.

A novel ratiometric electrolytic BS has just been developed for the ultrasensitive and specific identification of Salmonella in foods (Zheng et al. 2023). The BS combines Salt-induced Rolling Circular Amplifiers (SRCA) with the Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) platform. The fundamental concept of detecting is based on the self-calibration of ratiometric electrolytic measurements to minimize either outside or inside disruptions, in addition to employing quick SRCA amplification technological advances and the trans cleavage capability of CRISPR for particular enhancement of signals.

A novel portable chemical luminescence BS was created to rapidly identify and measure the levels in wine and coffee samples directly outdoors (Kakkar et al. 2023). The smartphone-based BS was created by combining low-cost, temporary analytic capsules that include a lateral flow assay strip with the chemiluminescence detecting mechanism of the smartphone camera acting as a light detection. Scientists have created a sensitive BS that does not require labeling (Hua et al. 2021). This BS is made using a 2D photonic crystal functionalized with aptamers. It can detect the presence of kanamycin in dairy. The BS has demonstrated outstanding accuracy by combining positively charged AuNPs and sulfhydryl-modified DNA, achieving a detection limit of 1.10 pg/mL. BSs that rely on the acetylcholinesterase enzyme for inhibition are often favored (Nunes et al. 2022). This is because the toxic effect of organophosphorus insecticides creates covalent bonds, which permanently deactivate the acetylcholinesterase enzymes. An electrochemical BS of graphene was developed to detect 11 different organophosphorus insecticides. The detection method used was an indirectly competitive approach. The BS was created through the phosphorylation of acetylcholinesterase using organophosphorus compounds, together with the high conductivity of monolayer.

Researchers have developed a BS utilizing graphene oxide to detect shrimp allergies caused by tropomyosin (Xiong et al. 2020). Research was conducted on developing BSs capable of detecting allergens and assessing the effectiveness of allergy medications. To enhance the signal, they developed bioelectronic sensors using tiny particles and anti-immunoglobulin E antibody sensors. Researchers created a BS made of paper that does not contain cells, which can be used to detect the presence of Hg^{2+} and Pb^{2+} in water at the location where the testing is being done. This BS combines in vitro transcriptional technologies with antagonistic transcription variables. A chemiluminescence BS using a hydroxy-ethylcellulose-based membrane to identify hydrogen peroxides in various dairy products, such as fresh-raw, complete, semi-skimmed, and skimmed dairy products. This is important because consuming excessive hydrogen peroxide can pose significant health risks.

Advantages and Dilemmas

Technology is essential for ensuring and guaranteeing food safety. The integration of traceability systems with BC has reached a pretty advanced stage, and implementing this integration at a technical level is now possible. The commercial deployment encompasses several elements, including technology installation, system integration, company restructuring, staff training, system assistance, maintenance, and upkeep. Despite progressing from proof of conception to significant commercial implementation, several problems must be confronted. There are several obstacles to implementing BC in fresh food.

(1) Regulating fresh food is a significant difficulty despite the potential for BC to partially optimize the economy's structure. BC’s decentralized and transparent nature has allowed unscrupulous individuals to exploit fresh food in the marketplace. The implementation of BC has made it challenging to effectively regulate and monitor the fresh food market, resulting in disorder.

(2) Due to the rapid advancement of science and technology, there is a growing concern that BC is vulnerable to being deciphered, posing a significant challenge to its security. The BC must ensure the integrity of the information and be able to surpass the limitations inherent in the records.

(3) The effectiveness and expenditure of resources. BC-based fresh food quality traceability incurs higher expenses compared to traditional cloud technology. As civilization expanded, the

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amount of data increased, and BC technology progressively proved inadequate for handling large-scale data exchanges and could be more efficient. Enhancing technology is necessary as the demand for BC continues to grow. The process of maximizing BC incurs a substantial expense.

(4) There needs to be standardized technical criteria. Several nations have submitted patent applications, but a definition for BC technological advances needs to be accepted, and more authoritative evaluation organizations must be established. This situation could cause uncertainty throughout the implementation of BC.

The benefits of employing BC in the fresh food industry are readily apparent.

(1) Implementing BC has significantly improved the dependability and openness of data in the FSC for fresh food. Networked and electronic storage models are implemented using various sensors and sophisticated technologies, enabling precise data analysis and rapid information traceability.

(2) Utilizing BC in the fresh food industry offers significant benefits and promising prospects. Implementing the entire system encounters several obstacles, resulting in the ineffectiveness of the practical utilization of BC. The government and stakeholders in the fresh BC ought to take a range of steps in many areas, encompassing but not restricted to: The government and stakeholders in the local BC should implement a range of initiatives in a comprehensive way, which includes but is not limited to, supporting the overhaul of the agricultural production infrastructures and enhancing investment in research and development to foster technical innovation and establishing an optimal setting to facilitate the growth and cultivation of perishable food items.

Results

The study has examined throughput, delay, and reaction time as efficiency evaluation metrics by employing the JMeter simulation toolbox for the suggested system. These assessments evaluate the effectiveness and dependability of the suggested technology. The research has included users ranging from 100 to 1000 for this outcome assessment. Figure 2 illustrates the evaluation of the data layer's throughput, latency, and reaction time. The x-axis of this chart represents the number of transactions, while the y-axis represents the throughput in throughput, latency, and reaction time in milliseconds. There is a direct correlation between the number of operations and throughput, with minimal fluctuations. In this context, better throughput refers to the ability of the suggested technology's data layer to manage many transactions effectively. Shorter latency suggests faster transaction execution and a more responsive network. The reaction time shows fluctuations, with certain transactions witnessing a rise while others observe a decrease.

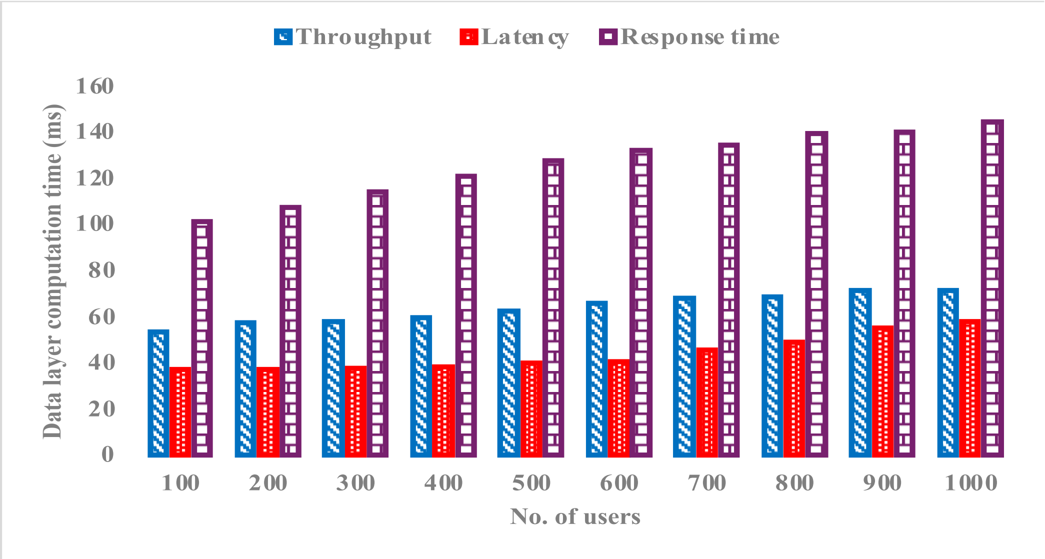

Figure 2. Data Layer Result Analysis

Figure 3 displays the performance metrics of the suggested BC layer system, including throughput, latency, and reaction time. It is evident that as the number of users increases, the throughput continuously rises, reaching its highest point at 700 customers. It undergoes a drop of 800 usages and then rises again to get a range of 900-1000 customers. The latency and reaction time continuously remain low, with little fluctuations during the transaction.

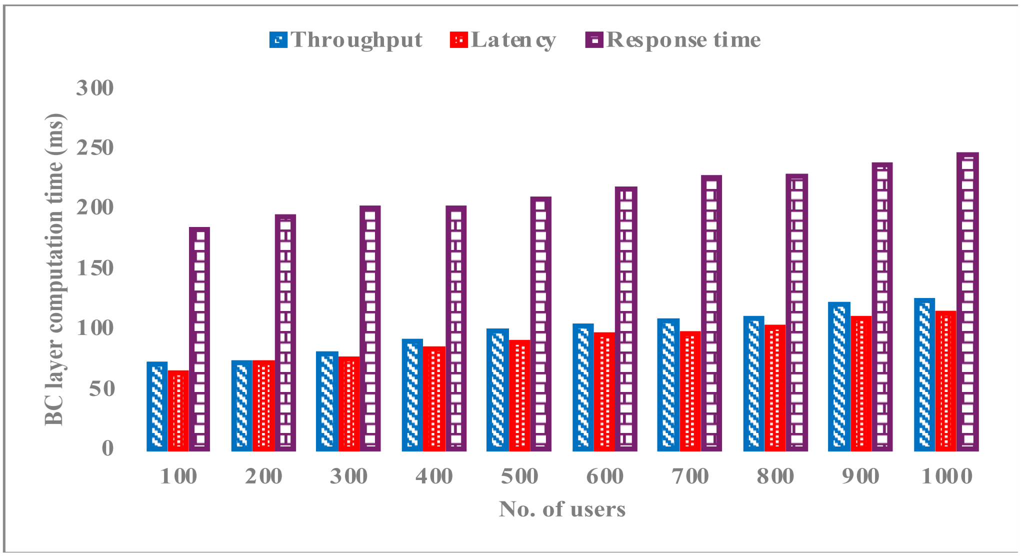

Figure 3. BC Layer Result Analysis

Figure 4 displays the performance metrics of the suggested structure navigation layer, including throughput, latency, and reaction time. The throughput exhibits a steady rise as the number of customers grows, reaching a peak at 700 customers. However, after this point, the throughput becomes unstable and fluctuates. The latency and response time remain continuously low, with few changes during the transaction.

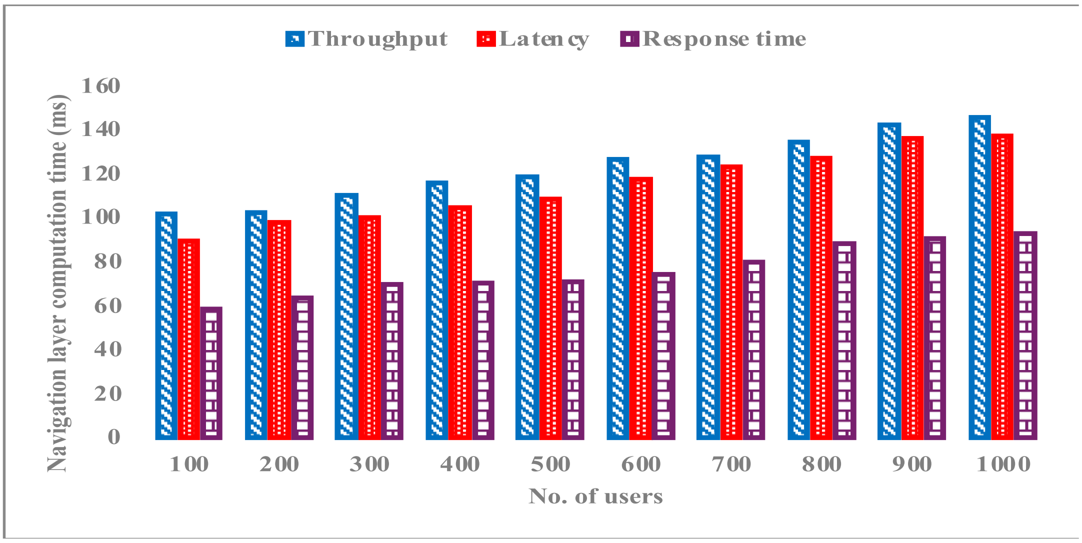

Figure 4. Navigation Layer Result Analysis

Figure 5 displays the suggested approach's throughput, delay, and reaction time. Delay and reaction time stay continuously low with slight variations during the transaction while the throughput swings. This figure 5 provides a convenient way to determine the mean values of each measure for different setups. The investigation determined that the mean throughput is 383.24 Transactions Per Second (TPS), the mean delay is 41.32 ms, and the mean response period is 79.25 ms. The Data Layer controls data storage, retrieval, processing, and consistency; Figure 2 displays the correlation between user count and calculation time in this layer.

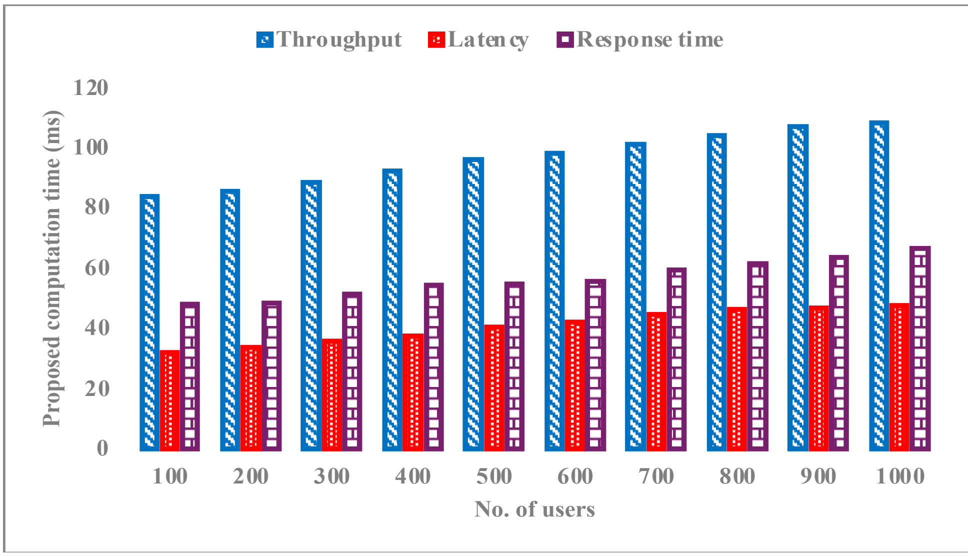

Figure 5. Overall Performance Analysis

Computation time in the Blockchain (BC) Layer—which includes cryptographic operations, consensus procedures, validation of transactions, and data storage in a decentralized ledger—depends on the number of users, as shown in Figure 3. The number of users and the amount of time it takes for the Navigation Layer to compute their positions, plans their routes, and makes navigational decisions are shown in Figure 4. Figure 5 shows that the relation between number of users Vs proposed model computation time. For all these Figures, the processing time required to manage database changes, queries, and transactions grows in direct proportion to the number of users. When compared to the previous model, the proposed model is having minimal computation time, response time and higher throughput.

Conclusions: The growing occurrence of foodborne diseases and lack of access to sufficient food has created a pressing need to develop efficient food traceability methods that are fast, precise, dependable, cost-effective, and capable of performing numerous tests. Significant progress in BS technology has demonstrated considerable potential in allowing comprehensive tracking of the entire BC to address the challenges posed by its unpredictability and complexity. The technological characteristics of BC, including decentralized governance, data immutability, anti-forgery and traceability, and trust processes, align well with the requirements of a fresh food tracking system. Implementing a BC-powered platform for tracing the FSC of nutritious food can effectively accomplish the objectives of tracing the origins of food, tracking its movement, ensuring information transparency, and establishing accountability. This will enhance food security and reliability while decreasing the operational expenses associated with the BC. This study focuses on several methods of creating BSs for use in food production's pre- and post-harvest stages. These methods include applications in farming, the detection of biological and chemical pollutants in food, and the development of intelligent packaging for food. According to the present patterns, several BSs linked to nanoparticles provide several benefits, including a reduced limit of detection, enhanced sensitivity, selection, and long-term resilience. Several obstacles remain to be addressed and improved in the future.

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افزایش کیفیت غذا و قابلیت ردیابی از طریق ادغام حسگرهای زیستی و فناوری بلاک چین

آبیجیت مادوکار هاوال

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چکیده

هدف: آلودگی مواد غذایی و ضایعات مواد غذایی به طور قابل توجهی در افزایش بروز بیماری های ناشی از غذا و کمبود مواد غذایی در سطح جهان نقش داشته است. یک ضرورت مبرم برای ایجاد یک سیستم ردیابی مواد غذایی هوشمندتر وجود دارد. پیشرفت های اخیر در فناوری حسگر زیستی (BS) منجر به توسعه BS های کاربرپسند، سریع، خاص، بسیار حساس و مقرون به صرفه شده است. این پیشرفت‌ها دارای پتانسیل قابل توجهی در رسیدگی به نیاز فوری به تشخیص و درمان سریع مسائل مربوط به امنیت غذایی و کنترل کیفیت هستند که معمولاً به عنوان فناوری‌های نقطه مراقبت از آن یاد می‌شود. بلاک چین (BC) یک رکورد غیرقابل تغییر و به راحتی قابل مشاهده ارائه می‌دهد که مزایایی را در قابلیت ردیابی کیفیت غذای تازه و نظارت بر آن در زمان واقعی به ارمغان می آورد.

نتایج: این مقاله به بررسی ارتباط بین قبل از میلاد، قابلیت ردیابی و نظارت بر کیفیت غذا در زمان واقعی می‌پردازد. این آخرین پیشرفت‌های فناوری در ردیابی مواد غذایی و نظارت مستمر را نشان می‌دهد که می‌تواند داده‌های ارزشمندی را برای اجرای BC ارائه دهد. بحث بر روی استفاده از BSs در کشاورزی در مرحله قبل از برداشت برای شناسایی و مدیریت بیماری‌ها یا تنش‌های گیاهی در مرحله اولیه متمرکز است.

نتیجه‌گیری: این بررسی بر پیشرفت اخیر در BSs در زنجیره تامین غذا (FSC)، به ویژه در مرحله پس از برداشت تمرکز دارد. این پیشرفت ها در تشخیص انواع مختلف آلاینده‌های غذایی و توسعه بسته بندی هوشمند مواد غذایی را برجسته می‌کند.

واژه‌های کلیدی: بلاک چین، حسگرهای زیستی، قابلیت ردیابی، کیفیت غذا

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