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IoT Technology as an Effective Strategy Enhances Food Authentication for Current Fresh Fruit Supply Chain

Yiqin Zhang^{1,2,3} | Simin Fan^{2,3} | Ruiling Liu¹ | Huizhi Chen¹ | Ben Niu¹ | Hangjun Chen¹ | Weijie Wu¹

¹Zhejiang Key Laboratory of Intelligent Food Logistic and Processing, Key Laboratory of Post-Harvest Handling of Fruits, Ministry of Agriculture and Rural Affairs, Key Laboratory of Postharvest Preservation and Processing of Vegetables (Co-Construction By Ministry and Province), Key Laboratory of Postharvest Preservation and Processing of Fruits and Vegetables, China National Light Industry, Food Science Institute, Zhejiang Academy of Agricultural Sciences, Hangzhou, China | ²College of Food Science, Sichuan Agricultural University, Yaan, China | ³Laboratory of Biomass and Green Technologies, Gembloux Agro-Bio Tech, University of Liège, Gembloux, Belgium

Correspondence: Hangjun Chen (spshangjun@sina.com) | Weijie Wu (wuweijie87@163.com)

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ABSTRACT

With trade globalization, food fraud such as tampering, substituting, and falsifying, challenges human health and the management of food supply chain. As a food type that only processed at primary level, the authenticity of fruit supply information has become a guarantee for its edible safety. This review covers recent applications of IoT technologies in fresh fruit supply chain (FFSC) management, focusing on their potential to authenticate fruit information, predict shelf-life, and improve supply chain efficiency. Besides, the technical evaluation and application barrier analysis are also conducted. Results showed that IoT can comprehensively improve the service level of the FFSC. Concretely, wireless sensors can record the whole supply information of fruits on cultivation, picking, processing, and transportation. Moreover, fruit quality authentication and shelf-life prediction are carried out by mathematical coupling models in remote monitoring database. Such information can be furtherly distributed and encrypted through blockchain and other encryption techniques, resulting in secure, permanent, and immutable food authentication information, thereby greatly avoiding the food fraud behaviors. However, the application of these emerging technologies still faces challenges of technical obstacles, infrastructure construction, and model optimization for commercial use.

1 | Introduction

The World Economic Forum (WEF) reported that nearly 10% of the population worldwide gets sick due to food safety incidents, involving substituting, diluting, falsifying food ingredients, and misleading statements about food (WEF 2019). In the background of the global outbreak of SARS-COVID-19, people seem to be more concerned about the safety, quality, and nutrients of food, especially those agri-food that only undergoes minimal

processing, such as fruits (Salman et al. 2021; Thomas et al. 2021). Thus, fruits that are being safe to eat, harvested from a high-quality origin, and rich in nutrition are increasingly sought after by consumers.

However, food fraud behaviors pose risks to the edible value and safety concern of fruit. Food fraud commonly manifests in several specific forms, including but not limited to varietal substitution, origin mislabeling, ripeness deception and

Yiqin Zhang and Simin Fan Authors contribute equally.

Yiqin Zhang and Simin Fan Co-First authors.

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specification fraud (Das et al. 2025). For example, the mislabeling of cherries from the Brda region of Slovenia as “Italian produce”, due to the higher market price of Italian cherries, is a typical case of geographical indication fraud (Mahynski et al. 2025). During postharvest fresh fruit supply chain (FFSC), fresh fruits are prone to mechanical damage, peel browning, pulp softening, nutrients deterioration, and pathogen infection (*Botrytis cinerea*, *Alternaria alternata*, *Penicillium species*, etc.) (W. Zhang and Jiang 2019; Bunge et al. 2022; W. Zhang et al. 2023; Y. Zhang et al. 2023a). In this process, many suppliers tamper with the inherent fruit information to replace, such as origin, picking date, and circulation mode. This makes it impossible to get the real information about the fruit from the label, leading to confusion in the market. Furthermore, participants in fruit trade are widely distributed, warranting a third-party centralized server (client paradigm) to guarantee the transaction information (including data storage, transmission, and sharing) from producer till it reaches consumers (Duan et al. 2024). However, there is still the possibility of data tampering, leading to trust crisis among complex stakeholders (M. A. Khan and Salah 2018), making the fruit source, processing, and transaction information ambiguous (Kamilaris et al. 2019). On the other hand, part of orchards uses excessive and chemically synthesized pesticides (dichlorvos, phoxim, hexachlorocyclohexane, etc.) to increase fruit production. This not only reduces safety level of fruits but also deteriorates the ecological environment (Xu et al. 2022). Based on the above phenomenon, many studies advocate transparent and sustainable production for FFSC to improve consumers' edible safety, value perception, and willingness to pay for high-quality fruits (Y. Zhang, Chen, et al. 2022).

In fact, as the institutional economics clarified, the information constraints and insufficient recognition have become major deficiencies in the agri-food industry. These issues increase the difficulty of transactions, leading to inefficiency and adulteration in FFSC, and ultimately cause a loss of food quality and consumer trust (Kamble, Gunasekaran, and Gawankar 2020a; Kamble, Gunasekaran, and Sharma 2020b; Z. Liu et al. 2021). Figure 1 summarizes the process of the current fresh fruit supply chain in general situations. To this end, the Food and Agriculture organization (FAO) conducted E-agriculture, that is, applying Internet of Things (IoT) into agri-food area to improve food authentication, transaction information sharing, supply efficiency, and service quality (Ferrag et al. 2018; X. Li et al. 2020). Kitouni et al. (2018) proposed an approach for effectively integrating the IoT into agricultural enterprises including smart sensors and agricultural machinery. The approach was based on agent interaction protocols (AIP), through which they specified complex transactions by recognizing large meaningful code chunks (generated automatically by webpack) in the application domain. In another study, Mukherjee et al. (2018) also reported an agricultural IoT to solve sustainability issues such as transaction fraud and fruit rot. The study proposed a method of sensor authentication and blind agricultural IoT node, which could be sourced and operated from the master node or remote monitoring center. It can be seen that FFSC integrated with IoT technologies has become a potential trend to enhance food authentication and increase the efficiency of circulation.

In recent years, there has been an explosion application of IoT in the agri-food supply chain, literature focusing on traceability, automated trading models, and high-precision sensing materials. However, there are no comprehensive reviews on the IoT enhancing fruit information authentication. Herein, this paper summarizes recent applications of IoT-related technologies in agri-food supply chain and introduces the potential of these technologies for the authentication of fruit identity and quality, the prediction of fruit shelf life, and the enhancement of FFSC service. Additionally, the systematic evaluation and application barriers highlighting their advantages and limitations are emphasized with future needed developments.

2 | Sensing Technology

Ideally, nondestructive quality sensing technologies are effective means to enhance fruit authentication and prolong fruit quality in FFSC. The characteristic of such technologies is that they can rapidly assess fruit quality and ripeness through physical or chemical methods without damaging the external appearance or internal structure of the fruit (Akter et al. 2024). The sensing technology is in the law of indirect detection and its basic procedure includes the following: (1) acquiring the electronic signals of the FFSC microenvironment via sensor elements; (2) converting electronic signals into readable data; (3) building the correlation model between data and fruit (authentication, quality, and predictive value) via experimental measures; (4) predicting fruit quality and trading based on the built model (X. Wang et al. 2021). Selecting appropriate sensing technologies in the FFSC first requires an understanding of the fundamental principles of these specific technologies. The selection criteria are based on the compatibility with the target fruit, the application scenarios, and their potential impact on monitoring fruit quality and safety. For example, gas sensors and electronic noses/tongues are highlighted for their sensitivity to volatile organic compounds and flavor profiles, which are critical indicators of fruit freshness and spoilage. Optical sensing technologies were chosen because of their rapid detection capabilities. Literature demonstrated that many sensing technologies with high resolution and smart systems have been developed in recent years (Le et al. 2016; Y. Zhang, Li, et al. 2022). These authentication technologies have greatly improved the efficiency of FFSC.

2.1 | The Commonly Used Gas Sensors

Generally, the use of nondestructive, contactless, and real-time quality sensing technologies are critical measures for fruit authentication and freshness prediction in the FFSC (X. Wang et al. 2021). The principle of sensing technology lies in detecting environmental parameter signals and then simulating and predicting the sensory and quality of fresh fruit via mathematical coupling model (S. Khan et al. 2023). Early research focused on high-resolution quality sensing via temperature and humidity, which were mostly based on the principles of thermal resistance, thermocouple, and thermoelectric capacity (X. Wang et al. 2021). Recently, studies began to focus on emerging and

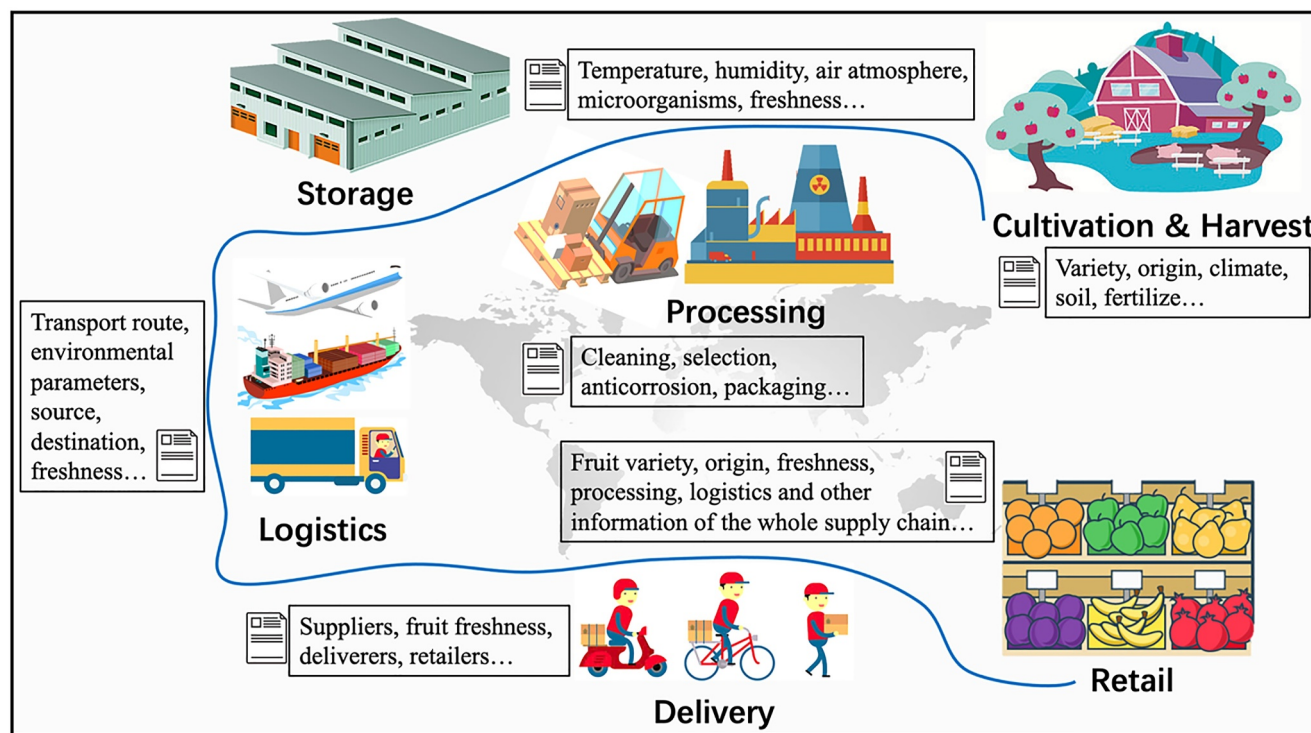


FIGURE 1 | The process of current fresh fruit supply chain in general situations.

more efficient sensor substrate materials. For example, Y. Zhang, Li, et al. (2022) prepared multifunctional silver-based metal-organic frameworks@carboxymethyl filter paper (Ag-MOFs@CMFP) composite paper by using in situ synthesis. The prepared composite paper could transmit the humidity response signal to the mobile phone thus providing remote real-time authentication of fruit quality (fresh strawberries, blueberries, and plums). Compared with temperature and humidity, the interaction between environmental gas and fruits is rather dynamic and uncertain (X. Wang et al. 2021). The postharvest fruit still keeps an active metabolism, mainly including respiration, transpiration, and stress-secondary metabolism, which are essential to maintain cell integrity and energy supply (ATP, ADP, and AMP) of the tissue (S. Li et al. 2021). These processes involve the exchange of various gas components, such as O_2 , CO_2 , H_2O , ethanol, ethylene, volatile terpenes, aldehyde, and organic acids (He et al. 2022). Moreover, postharvest techniques are usually used to inhibit respiration, microorganisms, injury ethylene, and other negative effect factors to reduce enzymatic browning and maintaining the oxidation reduction (REDOX) homeostasis of fruits, and ultimately prolong fruits shelf life (Zhu 2016; S. Li et al. 2021). Such diversified preservation technology of modern cold chain increases the complexity of the gas environment of FFSC (Figure 2), such as 1-MCP, NO , O_3 , H_2S , ClO_2 , and SO_2 gas fumigation, controlled atmosphere, and edible coating (W. Zhang and Jiang 2019). For the most part, the industrial gas sensor array cannot meet the requirement of micro signal acquisition for FFSC due to its limitations of resolution, scale, power consumption, cost, and so on (X. Wang et al. 2016; S. Khan et al. 2023).

In the environment of FFSC, even some micro variations of gas may cause significant changes in fruit status, thus bringing

many uncontrollable factors for fruit quality authentication (He et al. 2022). For example, the reduction of local O_2 concentration can lead to anaerobic respiration of the fruit, resulting in ethanol and unpleasant smell (Y. Zhang et al. 2021; W. Zhang et al. 2023; Y. Zhang et al. 2023a). Studies have demonstrated that α -farnesene and conjugated trienols could act as endogenous inducers which were intrinsically correlated with fruit peel browning (Lindo-García et al. 2021), and has yet to be revealed for other natural products in fruits. In addition, ethylene is an autocatalytic plant hormone that accumulates in the transport environment of FFSC, thus accelerating fruit senescence (S. Li et al. 2021). To this end, the monitoring and regulation of FFSC gas environment is considerable to be a prerequisite to maintain the shelf life and authentication of fruit cargo (Y. Zhang, Li, et al. 2022). However, the FFSC typically operates in low-temperature and high-humidity environments, where gas sensor drift often exceeds acceptable accuracy limits. In such conditions, water molecules may adsorb onto the sensor surface, occupying active sites and hindering the adsorption of target gases. Furthermore, low temperatures can slow the sensor's reaction rate, leading to longer response times and reduced sensitivity. Moreover, sensors require self-power support for online detection and authentication of fruit quality (X. Wang et al. 2021).

With the boom in semiconductor and spectroscopic technology, gas sensors based on different principles are gradually developed, types could be broadly classified as electrical, optic, surface acoustic wave, gas chromatographic and calorimetric-based sensors (Xiao, Mu, et al. 2022). Metal-oxide semiconductors (ZnO , SnO_2 , WO_3 , and MOS), carbon- and silicon-based materials (carbon nanotubes (CNT), graphene oxide (GO), and lamellar silicate), and electrochemical (conductive hydrogel)

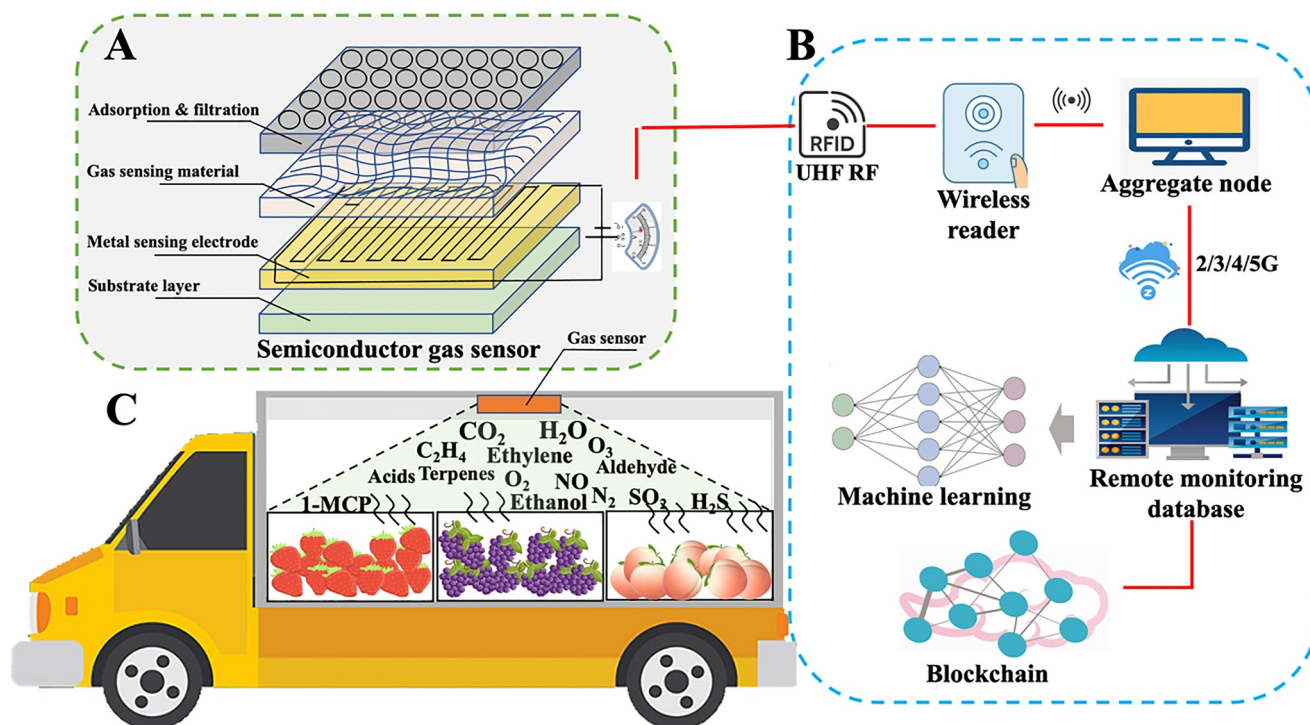


FIGURE 2 | A typical sensor system in the fresh fruit supply chain. (A) represented the component and working principle of the semiconductor gas sensor, (B) was the propagation path and reading process of the sensor electrical signal, and (C) showed the main gas atmosphere of the fruit during storage and transportation.

can sense changes in electrode properties (Xiao, Mu, et al. 2022; S. Khan et al. 2023). These sensing technologies greatly enhance the authentication of the food supply chain. For example, most of MOS gas sensors are based on the adsorption and reaction of the target gas to be measured by MOS gas sensitive material, which causes the successive change of charge carrier and resistance value. Then the electrical signal is captured in current/voltage change, and finally read by computer through the analog-to-digital conversion (ADC) (Dey 2018). The basic components and sensing principles of semiconductor gas sensors were shown in Figure 2. Sensors based on optic properties can be further divided into near-infrared spectroscopy, Raman spectroscopy, hyperspectral, and x-ray fluorescence spectroscopy. Similarly, these technologies are mainly sensing signals through the changes of absorption of light by hydrogen-containing groups of organic compounds, Raman scattering and displacement and the release of x-rays from atoms excited by high-energy radiation (X. Wang et al. 2021; S. Khan et al. 2023).

Although various gas sensors have been developed for particular gas species, such as biogenic amines, pH values, and foodborne pathogens. With the FFSC upgrade, future sensors should be oriented toward flexible sensor platforms, sensitivity and responsiveness optimization, manufacturing technologies (microelectron mechanical system and 3D printing), multiple components and full functionality (multi-sensor arrays) toward all gas species in fruits. In a study of Thai et al. (2020), the multi-sensor array could monitor multiple parameters in FFSC to obtain more effective environmental and fruit information.

2.2 | Smart Tag Systems With Color Response

In addition to gas sensors, smart tags that rely on color response can also monitor environmental parameters and certify fruits' nutritional quality upon storage and transportation. They can indicate more visible fruit freshness for the B-ends (business) and C-ends (consumer) of the FFSC (He et al. 2022).

Recent studies have focused on gas target metabolite products, gas sensitive components, and their underlying interaction mechanisms. The types of gas metabolites have been discussed in Section 3.1. Gas-sensitive components consist mainly of chemical or natural pH chromogenic dyes (indicators), as well as some nonferrous metal ions. Early colorimetric indicators on chemical synthesis mainly include methyl red, phenol red, bromophenol red/blue, and bromocresol purple. The principles of chemical reactions involve Lewis acid/base and dipole reactions. For example, the color change of phenol cyanogen dye during deprotonation (He et al. 2022; S. Khan et al. 2023). Natural pH indicator dyes mainly belong to anthocyanins and betalains extracted from plants such as roselle and beetroot. These dyes depend on their chemical structure changes caused by the positively charged oxygen (IV) and nitrogen (III) atoms, thus inducing different colors (Becerril et al. 2021). Their chemical structures were shown in Figure 3. The main nonferrous metal ions include Mn (II, IV, VI and VII), Mo (III, IV, V, and VI), and Cr (II, III, and VI), and they show different colors in different valence states (Iskandar et al. 2020).

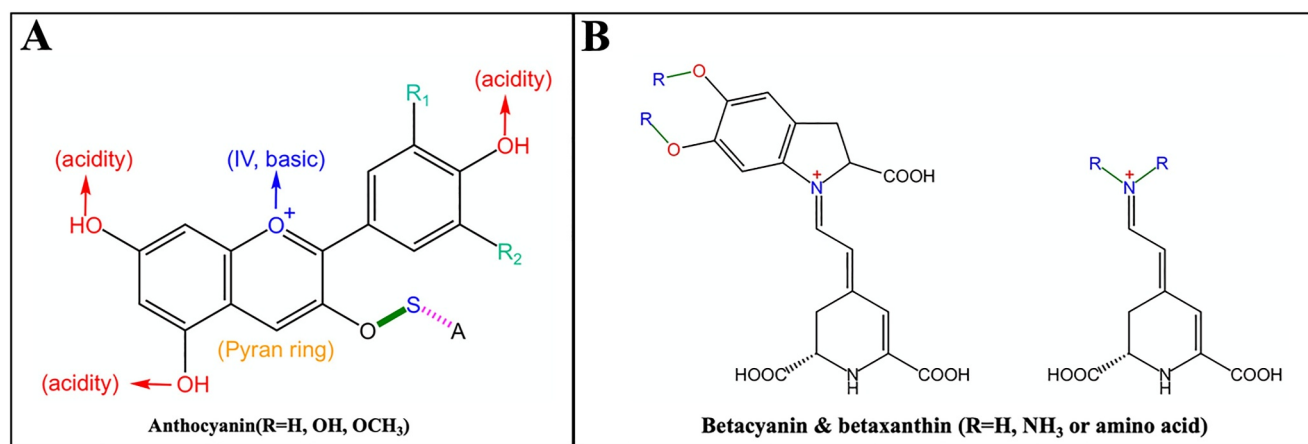


FIGURE 3 | Chemical structure and active sites of anthocyanin (A) and betalain (B).

Studies on CO₂ analysis is relatively comprehensive compared to other gases. Wan et al. (2021) explored the application of succinylated chitosan and hydroxypropyl chitosan film (bromocresol blue and methyl red as indicators) to monitor and identify the modifications in banana during storage at 10°C. In their study, the label film color difference (ΔE) from blue (fresh) to yellow (not fresh) showed a good linear relationship with the CO₂ content which could predict the ripening and freshness of the banana. The volatile organic acids of fruits are mainly low carbon straight-chain fatty acids, such as formic acid, acetic acid, and butyric acid produced from Embden–Meyerhof pathway (EMP) (He et al. 2022). Kuswandi et al. (2013) evaluated the volatile organic acid content of guava by fixing bromophenol blue as an indicator on bacterial cellulose films by absorption method. With the extension of storage time, the film changed from blue to green allowing for a multi-parameter fruit quality authentication model, including soluble solid (TSS), texture, and sensory evaluation. Studies on natural pigments as indicators mainly focus on marine, meat, and dairy foods, with less application for fruits, which is also the focus of future research. In an interesting study by Zhou et al. (2021), smart labels containing blueberry anthocyanins and cellulose nanofibers (CNF) were prepared by coaxial 3D printing. With litchi freshness decreasing, the color of the label gradually changed from purple to pink. The 3D-printed label also had the function of sustained release on 1-Methylcyclopropene (1-MCP), which could extend the shelf life of litchi by 6 days. Likewise, an intelligent starch/chitosan-based film incorporated by anthocyanin-encapsulated amylopectin nanoparticles (ANPs) was fabricated for the determination of shrimp freshness monitoring. The pH-responsive films with ANPs exhibited obvious color changes from pink-colorless-yellow to reflect shrimp deterioration and yet to be examined for other food types. There are also natural plant extracts that have shown potential in monitoring fruit freshness. Ardiyansyah et al. (2020) prepared a pH-responsive colorimetric indicator packaging based on Brazilian hematoxylin extracts to successfully identify the quality of climacteric fruit (banana) within 6 days, showing the color from yellow (pH 4.5) to dark red (pH 5.1). Respiratory climacteric fruits such as apple, avocado, guava, and banana are sensitive to ethylene signal response, and for which monitoring of ethylene is particularly important. Pirsá and Chavoshizadeh (2018) developed a smart label based on bacterial

nanocellulose and KMnO₄ (oxidizing metal ions indicator), to measure ethylene levels in banana fruit during storage (i.e., red to yellow indicates a decrease in freshness). Other smart sensing tags application included the use of aldol condensation and Cannizzaro reactions to indicate volatile aldehydes in fruit (He et al. 2022).

In addition, high target specificity binding smart tags for bio-recognition probes have also become a hot topic in recent years. These tags were mainly used to monitor pesticide residues and foodborne microbial (including viable but nonculturable (VBNC) state) contamination for the authentication of fruits. Promising probes include bacteriophages, functional oligonucleotides, and antibodies (S. Khan et al. 2023). Y. Tian et al. (2021) proposed to immobilize *Alicyclobacillus acidoterrestris* specific aptamers and antibodies onto magnetic nanoparticles to isolate target bacteria in juices, and subsequently used *A. acidoterrestris*-binding antibodies labeled with fluorescent quantum dots for fluorescence visualization. It is necessary to mention the time and temperature indicator (TTI), which mainly uses the acetylene reagent to prepare the activity indicator, monitors the temperature accumulation effects through diffusion, polymerization, and enzymatic method, and then indicates food quality changing and remaining shelf-life information by combining the Arrhenius equation (X. Zhang et al. 2016; T. Gao et al. 2020). Bobelyn et al. (2006) evaluated the color change of mushrooms during cold chain, and a commercialized enzymatic TTI (Vitsab) was applied to check its applicability. The CIE color (L*) was used to identify the mushroom quality and the reflectance of the TTI was considered for modeling. Suppakul et al. (2018) designed a diffusion type TTI which employed polydiacetylene/silica nanocomposite (PDA/SiO₂ NC) as the color-developing substance, and it was loaded on the diffusion path of a microporous strip. This designed TTI produced good results in the quality authentication in wheat grass juice.

2.3 | Electronic Nose and Electronic Tongue

Electronic noses (E-noses) and electronic tongues (E-tongues) have emerged as innovative sensor tools for enhancing quality

authentication and safety monitoring in this sector. These devices simulate human olfactory and gustatory senses, providing nondestructive and rapid methods for analyzing various attributes of fresh fruits (Baldwin et al. 2011). Specifically, E-noses are particularly effective in assessing the ripeness and freshness of fruits by detecting VOCs emitted by produce. For instance, they can identify the presence of ethylene, a key hormone in the ripening process, allowing for precise timing of harvesting and storage conditions (Tibaduiza et al. 2024). E-tongues, on the other hand, analyze the taste profile of fruits and vegetables by detecting nonvolatile compounds. This capability is crucial for ensuring consistency in flavor and sweetness levels, which is essential for processed fruit products (Tibaduiza et al. 2024).

The spoilage detection also takes an important sector in minimizing waste and maintaining consumer satisfaction. E-noses and E-tongues can identify changes in VOC profiles, pH levels, and acidity that occur as fruits begin to decay, enabling timely intervention such as adjusting storage conditions or prioritizing the sale of produce that is nearing spoilage (Munekata et al. 2023). Importantly, the E-noses and E-tongues contribute to optimizing logistics and distribution in the wide abroad supply chain. By providing real-time data on the quality and condition of produce, these sensors enable better decision-making regarding transportation routes, storage durations, and inventory management. In addition, the integration of E-noses and E-tongues with other data analytics and machine learning techniques can further enhance their capabilities. Advanced algorithms can process the data collected by these sensors to predict future quality changes and identify patterns that may indicate potential issues (Munekata et al. 2023). This predictive analytics approach allows for proactive measures to be taken, rather than reactive ones, thereby improving the overall quality and safety of the produce.

Of course, there are also challenges associated with E-noses and E-tongues, including issues related to sensor drift, sensitivity loss, and regular calibration. Besides, the complexity and cost of these devices can be barriers to widespread adoption, particularly for small-scale producers (Baldwin et al. 2011). Therefore, ongoing research and development are focused on creating more robust, cost-effective, and user-friendly versions of these technologies, ensuring them an important role in the safety, quality, and sustainability FFSC.

2.4 | Optical Sensing Technology

Sensors are mainly aimed at nondestructive monitoring and authentication of fruit metabolites in FFSC, whereas spectral imaging sensing technology is based on the surface and internal images of fruits for anti-counterfeiting and identity authentication, which can bring more impact and intuitive results. Inevitably, mechanical damage occurs during fruit postharvest processing in FFSC. One difficulty is that bruising may not be visible instantly as it may take a 12 h incubation period (Du et al. 2020). At the microscopic scale, it is manifested as the damage of the phospholipid bilayer in cell membrane and the fracture of the structural fibers in cell wall, which leads to

the disappearance of the compartment effect between enzymes and substrates, and the interaction of them eventually produces visible lesions on the fruit epidermis (W. Zhang and Jiang 2019). In addition, some fruits also undergo corkification and lignification, resulting in fruit spots (W. Zhang et al. 2023; Y. Zhang et al. 2023a). These internal and external features give the fruit a distinctive and unique texture that can be readily recognized. At present, new spectral sensing techniques create more possibility for fruit authentication, such as hyperspectral, fluorescence, biospeckle, and x-ray. Setting spectral sensing at specific nodes in FFSC can effectively enhance the accuracy of fruit identity authentication and quality prediction (Du et al. 2020).

Hyperspectral imaging (HSI) can provide the fruit sample both spatial and spectral signal of a certain wavelength range from each pixel (J. Li, Luo, et al. 2019). In practice, data need to be filtered via ML to identify wavelength range that best represents the fruit identity (Du et al. 2020). These representative wavelengths can be used to represent the different texture characteristics of different fruits, such as spot, mechanical damage, peel browning, so as to identify fruit in FFSC. The information contained in HSI can be extracted and analyzed according to its wavelength pattern (one-dimensional spectrum), spatial pattern (two-dimensional image), and hyperspectral image (three-dimensional data cube) (Du et al. 2020; Shen et al. 2023). Currently, hyperspectral images are usually divided into several segments including visible region, short-wavelength near-infrared region, and mid-wavelength near-infrared region. These electromagnetic spectrum segments are processed to reduce the dimensionality via multivariate data analysis such as PCA. Other supervised multivariate data analysis for classifying spectral images at a certain wavelength range include partial least squares discriminant analysis (PLS-DA), SVM, random forest, CNN, and other ML methods for finding the proper wavelengths to complete the fruit authentication (Du et al. 2020; Cai et al. 2023). Que et al. (2023) applied spectral feature coupled with grouped convolutional network for the authentication model of seed variety (Figure 4A). The study employed interval continuum removal (iCR), backward interval partial least squares (BiPLS), and interval random frog (iRF) to constrain the spectrum; then extracted physical and chemical features of each interval independently by group convolution (GC), all over to improve the accuracy and inference speed of seed authentication models. Cai et al. (2023) used HSI, CNN, and attention mechanism to acquire and analyze the hyperspectral images from the two sides of Baishao known as Chinese peony. *Cynanchum otophyllum* Schneid, a TCM formulation used to treat inflammatory disorders for the accurate identification of its geographical origins. In this study, generalized gradient-weighted class activation mapping (Grad-CAM++) was utilized to visualize and identify certain wavelengths which were representative. The proposed data-level and feature-level deep fusion models outperformed the conventional ML methods in authentication of Baishao origins.

Speckle imaging refers to high-resolution imaging techniques based on displacement stacking or speckle interferometry. Biospeckle imaging is often used to observe discontinuous subcellular structures, such as filamentous, fibrous, softened, and pulpy biological tissues, in the practical application of FFSC authentication. This allows real-time image analysis of the FFSC

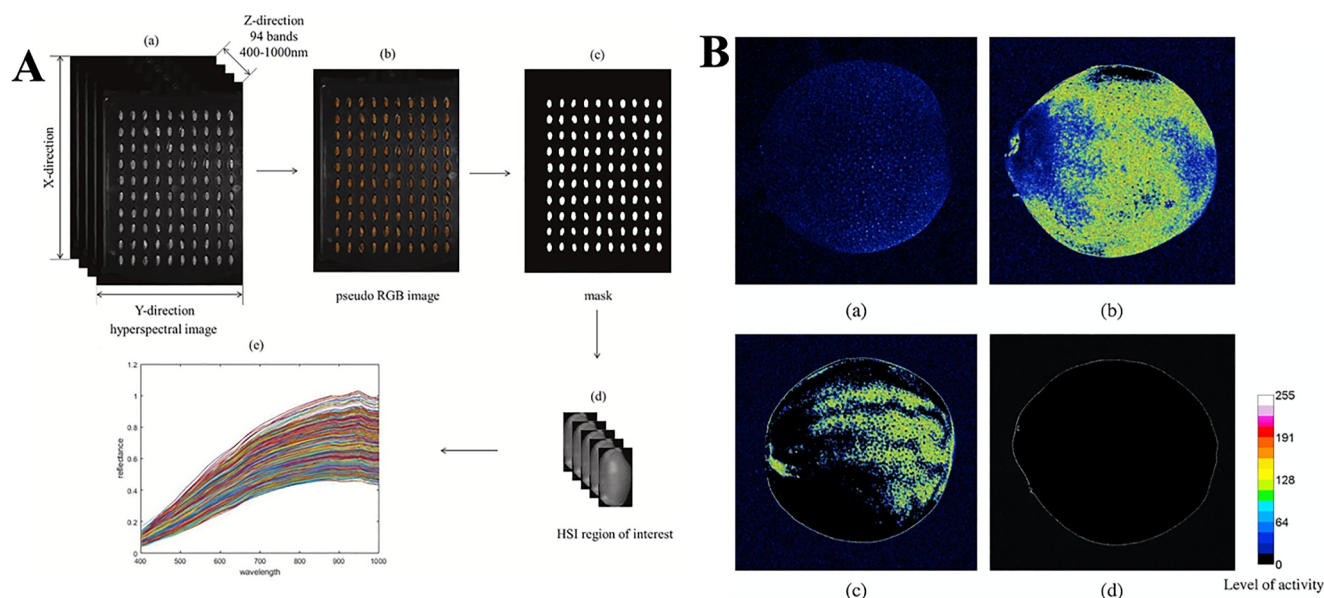


FIGURE 4 | Application of spectral imaging sensing technology in authentication of agri-foods. (A) Included the original hyperspectral image of wheat kernels, Pseudo RGB image, binary image for extracting regions, hyperspectral image cube, and raw spectra; (B) represented the bio-speckle activity image of citrus at different degrees of freezing visualized by Fujii method. Copyright 2023 & 2020 Elsevier. (A) Reproduced with permission from Que et al. (2023). (B) Reproduced with permission from Que et al. (2023) Rahmanian et al. (2020).

dynamic system to understand the physiological state of the fruit (Du et al. 2020). Specifically, organelle movement, cytoplasmic flow, and various biochemical reactions occur all throughout in fruit cells. The coherent laser irradiation causes optical interference between these dynamic intercellular/intracellular particles of fruit, resulting in diffuse reflection to form a group of dynamic random bright and dark spots (discrete spots) (Rahmanian et al. 2020). The mainstream speckle analysis methods include laser speckle contrast analysis (LASCA), generalized difference (GD), Fujii method, time contrast (TC), and inertia moment (IM) (Du et al. 2020). Rahmanian et al. (2020) extracted 12 features from oranges bio-speckle images for classification and authentication (Figure 4B). The classifiers included soft independent modeling of class analogy (SIMCA), linear discriminant analysis, quadratic discriminant analysis, ANN, and SVM. Their results of image processing proved the forward-scattering arrangement and ANN classifier resulted in the best prediction power with equal classification accuracies of 100%, which could be considered an alternative and useful tool for fruits authentication. Pieczywek et al. (2018) employed optical sensors and the artificial inoculation of apple fruit with *Pezizula malicorticis* (apples bull's eye rot) to identify the infection symptoms before it is visible. The chlorophyll fluorescence and globally measured bio-speckle activity and hyperspectral imaging enabled statistically significant detection of infected areas as early as 2 days after the inoculation of *P. malicorticis*. In addition, the spatial visualization of bio-speckle activity revealed the development of disease with a higher level of detail than hyperspectral imaging and allowed for the earlier infection detection than chlorophyll fluorescence detection method and has yet to be tested for other infections in different food matrices.

For some chlorophyll-rich, thin-skinned fruits, authentication can also be achieved by using fluorescence imaging. Fluorescence imaging is based on that chlorophyll emit fluorescence near the peaks of 685 and 730 nm when excited by electromagnetic radiation or visible light (Pieczywek et al. 2018). Therefore, database can identify counterfeit fruits according to the different distribution position and relative intensity of chlorophyll fluorescence in fruits (Du et al. 2020). Omwange et al. (2021) examined extra virgin olive oil (EVOO) adulterated with virgin olive oil (VOO) using front-face fluorescence spectroscopy and ultra-violet (UV) LED. In this study, excitation emission matrices (EEM) and their corresponding fluorescence images were captured and examined. Specific regions for both EEM and fluorescence imaging were classified using SVM and the sensitivities were evaluated using partial least squares regression (PLSR) analysis. Results showed that the front-face fluorescence spectroscopy and UV-induced fluorescence imaging could potentially discriminate adulterated olive oils.

Moreover, characteristic biometric fingerprints image (CBFI) based on visible light, structured illumination reflectance imaging (SIRI) using x-ray imaging (XI) based on the differences of attenuation in different fruit tissues, etc., have also shown great potential in fruit authentication. Nuclear magnetic resonance imaging and spontaneous thermal imaging can not only be used for fruit identity authentication, but also achieve quantification and correction of recognition error rates (Du et al. 2020; Shen et al. 2023). It is worth mentioning that although these emerging frontiers technologies can achieve anti-counterfeiting of fruits, cost, industry support, fruit type, and transportation distance are challenges that must be considered (Kamilaris et al. 2019; Y. Zhang, Chen, et al. 2022). In FFSC, we should

choose appropriate imaging sensing techniques based on the actual situation.

3 | Other IoT Technologies for Enhancing Fruit Authentication

3.1 | RFID

The development of wireless sensing technology has greatly improved the transparency of FFSC and ensured food quality and safety. However, the low efficiency of conventional cell let the system powering in long-term cold environmental FFSC become a problem. Fortunately, the RFID can realize fruit monitoring and authentication on dynamic nonstop information such as the gas composition, temperature and humidity, microorganism, and production date, place and batch without battery (antenna) (Le et al. 2016; Xiao, Mu, et al. 2022). RFID technology has been considered to be an enhanced method for temperature monitoring in food owing to several applications and benefits.

A typical wireless RFID system consists of tag, reader, signal processing circuit, and a microcontroller which can realize signal wireless acquisition, amplification, filtering, analog-to-digital conversion, power supply management, and other functions of data (Xiao, Mu, et al. 2022). The information and RF energy can be transmitted between the reader and tag within a few centimeters via an electromagnetic field. These collected data are then reliably transmitted to the aggregate node, and further to the remote master computer by GPRs, 2/3/4/5G and other means. The master computer processes the obtained data so as to issue control commands to the nodes in the FFSC (Figure 3). In addition, RFID have a sufficient nonvolatile memory that can be easily and nontamperably read/written by the reader (Xiao, Fu, et al. 2022; Xiao, Mu, et al. 2022). Therefore, RFID can be easily employed in FFSC for fruit monitoring, tracking, authentication, and cold chain management (X. Wang et al. 2021). Le et al. (2016) developed a battery-free 13.56 MHz-based RFID sensor tag to read monitoring data in the RF range of up to 30 cm and was employed to remotely control the transport environment of apricot abalone mushrooms. Recently, high frequency/ultra-high frequency (HF/UHF) RFID, which can read data with large throughput, strong penetration, large memory capacity, and more reliability, has increasing attention in food technology worldwide. Xiao, Fu, et al. (2022) proposed a sustainable battery-free sensing system for fruit cold chain management. The system transmitted fruit environmental data via UHF RFID and ZigBee, and collected solar energy to power sensing elements, readers, and sink nodes. With the continuous maturation of RFID, future research should focus on flexible RFID materials and multi-sensor integrated RFID, optimizing the early warning model to continuously monitor the fruit transport environment in FFSC (X. Wang et al. 2021).

3.2 | Mathematical Coupling Model and Remote Monitoring Databases

Another important aspect of fruit authentication is the signal processing method. Most of the studies placed signal processing

in remote monitoring database which includes the application layer, network layer, and database layer. Specifically, the application layer (basic database) is for user's authorization management, the network layer (communication database) is for communication management and the database layer (storage database) is for sensing data real-time monitoring and storage (Le et al. 2016; Xiao, Fu, et al. 2022). All the data existed in the database will be uploaded to the blockchain node in real-time. The user can get their required results by interaction with application layer and the database layer by the internet (Baralla et al., 2021).

The widely used analysis tools for databases include principal component analysis (PCA), independent component analysis (ICA), nonlinear principal component analysis (NLPCA), support vector machine (SVM), artificial neural network (ANN), back propagation neural network (BPNN), convolutional neural networks (CNN), Yolo neural network (YNN) and ML (Du et al. 2020). These data-driven machine learning models focus on automatically extracting features and patterns from large volumes of sensor data, offering strong real-time prediction and self-adaptive capabilities. Appropriately selecting models and analytical methods can enhance the accuracy of real-time environmental monitoring and improve system-level decision support in FFSC. Menichetti et al. (2023) introduced an ML algorithm (FoodProX) based on food processing extent classification system that accurately predicted the degree of food processing. In addition, predicting model of fruit freshness can be established based on the filtered data, and dynamic mathematical coupling algorithms involved include weighting, bias, linear/nonlinear coupling (X. Wang et al. 2021). Some mathematical coupling models of fruit quality based on different principles are shown in Table 1. Most of the existing mathematical modeling were derived from the respiratory rate, which only described relationship between O_2/CO_2 as fruit quality. There was an interesting work by Saenmuang et al. (2012), in which they successfully fitted 3 respiratory adaptability models of spinach under hypoxia environment according to Michaelis-Menten model, Langmuir adsorption model, with/without (competitive) inhibition. This model could be used for gas composition prediction and package optimization for spinach supply chain. Subsequent studies have introduced several different environmental parameters into the model to optimize the authentication results. Jalali et al. (2020) simultaneously considered microbial deterioration, mass loss and cumulative CO_2 production as a guide to predict the shelf life of strawberries. The model was applied in strawberry supply chain under modified atmosphere packaging and opening tray conditions with varying temperature and humidity. More recent studies were based on electronic nose discrete signal processing, which can separate hundreds of gas components to identify fruit quality (X. Wang et al. 2021), and further to infer for the sensory properties in food. However, dimensionality reduction analysis of the data is a challenge, and it is not suited for the continuous signal analysis with cumulative effects during the FFSC process. In general, to account for the complex interaction between gas and fruit quality, existing mathematical models need optimization to improve the prediction accuracy. Huang et al. (2023) proposed a groundbreaking method to use multi-sensing technology and ML algorithm to identify blueberry quality automatically and accurately. They investigated the interaction

TABLE 1 | The mathematical coupling model of fruit quality based on different principles and different parameters.

Species	Input parameters	Coupling quality	Mechanisms	Advantages	References
Mushroom	Temperature and relative humidity	Skin color change	Enzyme reaction kinetics	Integrated medium transfer and heat transfer process.	Joshi et al. (2018)
Apricot	Weight	Weight loss	Statistical method	Predicted the contents of carotene and phenolic.	Deng et al. (2022)
Lychee	Temperature and weight	Shelf-life prediction	Chemical reaction equation	Shelf-life at low temperature could be predicted.	Zou and Li (2020)
Strawberry	The pixel value for each area	Skin color change	Spectral analysis	Determined the effects of packaging, atmosphere, light, and air pressure.	Takemoto et al. (2022)
	Microbial deterioration, weight loss, and CO ₂ production	Shelf-life prediction	Michaelis–Menten equation	Coupled with multi-environmental parameters to improve accuracy	Jalali et al. (2020)
Spinach	Gas composition (CO ₂ , O ₂)	Respiration rate	Langmuir adsorption equation	Furtherly studied the information of respiration metabolism	Saenmuang et al. (2012)
Lettuce	Gas composition (CO ₂ , O ₂) and microbial population	Microbial growth rate	Michaelis–Menten equation	Microbial, quality attributes, and sensory scores were coupled during refrigeration	Yu et al. (2023)
Blueberry	Temperature and weight	Freshness prediction	Arrhenius equation and machine learning	Nondestructive sampling and machine learning could improve the accuracy of freshness prediction	Huang et al. (2023)
Garlic	Temperature, weight, gas composition, and packaging material	Respiration rate	Michaelis–Menten equation	Coupled with multi-environmental parameters to improve accuracy	Chen et al. (2019)

between O₂, CO₂, C₂H₄, and blueberry freshness at critical control points (HACCP) and further constructed neural network algorithms (BP, RBF, SVM, and ELM) for fruit freshness prediction. The four development methods all showed prediction accuracies above 90%, whereas the traditional Arrhenius equation method based on temperature and quality parameters was only at 85.10%.

3.3 | Blockchain

The blockchain is composed of a set of discrete client nodes based on the transmission control protocol (TCP) network, originating from the bitcoin digital currency white paper (Nakamoto 2008). In essence, blockchain is an intelligent peer-to-peer (P2P) network that uses a distributed database to identify, record and disseminate information ledger technology, with no restriction by geographic location factors. Specifically, it contains multiple dimensions of technologies, including the following. (1). Encryption technologies ensure data security, such as hash functions, asymmetric encryption algorithms, digital signatures, and anonymity techniques (Kamilaris et al. 2019). (2). Decentralized online discrete transaction technologies enhance transaction processing speed (C. Liu et al. 2018). (3). Electronic token technologies upgrade the traditional commercial currency model (Nakamoto 2008). (4). Transparent technologies record all transactions publicly on the internet, breaking the information asymmetry from the original centralized system (Rahman and Rahmani 2018). (5). Smart

contract technologies allow users to define operations of arbitrary complexity (Bunge et al. 2022). In this way, the anti-counterfeiting features of blockchain seem to meet the requirements of fruit authentication in FFSC. In fact, there have been extensive literature in recent years on the use of blockchain to enhance food authentication. With the governance level of hardware, software, networks, and database technologies developing in-depth, blockchain is expected to make the agri-food supply chain efficient, safe, and sustainable at the levels of society, environment, and economy (Y. Chen et al. 2020; Bunge et al. 2022).

(F. Tian 2016, 2017) proposed to integrate blockchain with IoT technologies (such as RFID, WSN, and near field communication (NFC)) for agri-food cultivation, harvest, processing, logistics, and sales, especially those key links during food processing, named hazard analysis and critical control point (HACCP). Such an approach using the smart sensors to automatically collect/upload data in real-time, thereby expanding the shared information set of all nodes in the entire supply chain. In their study, fruit information from FFSC was tracked, monitored, and stored, thereby providing a valuable information for fruit identity authentication. Since 2018, there has been increasing growth of blockchain-based applications, including industrial, medical, and agricultural programs around the world. Regarding agri-food literature were mainly centered on the supply chain whole process monitoring, decentralized transaction, information authenticity, sustainability, etc. For instance, Boehm et al. (2017) reported the use of more private NFC to track and identify food, providing great transparency

and security. Liao and Xu (2019) established a tea quality monitoring system based on blockchain. The program built a multi-role, multi-link production management system via E-agriculture. George et al. (2019) emphasized that the traceability has become the added value of food, which represented the quality of supply chain services and internal efficiency, and then they proposed to use blockchain and product identifiers to achieve food authentication in restaurants. In the field of agri-food trading, Mao et al. (2019) designed an automatic food trading system based on alliance blockchains (FTSCON), in which the online double auction mechanism was used to eliminate competition and the practical byzantine fault tolerance (PBFT, a consensus mechanism algorithm) was used to enhance service efficiency and food authentication. In this program, nonprofessionals could design and manage their own life-cycle smart contracts according to their needs, therefore, the authenticity and security issues in transactions were improved. Based on the aforementioned studies, many researchers even claimed that blockchain was a revolutionary information technology which presented great potential to enhance the food safety and authentication sustainably.

Transparency, authenticity, traceability as well as sustainability have become key indicators for evaluating the quality of the food supply chain. Distributed storage is a data management approach that distributes data across multiple physical locations to enable data sharing and collaboration, enhance data security, and reduce storage costs (Boller et al. 2024). It provides critical support in addressing data silos, improving transparency, and strengthening security. These issues that are particularly vital in the FFSC. Owing to the characteristic of distributed storage for anti-counterfeiting data, blockchain can reshape the traditional transaction mode of the current FFSC and respond quickly to the needs of growers, consumers, suppliers, and market supervision (Kamilaris et al. 2019). Monitoring of fruit quality, transparent transactions, information security and authenticity, and sustainable production are several critical factors for blockchain to enhance the fruit authentication in FFSC (Saurabh and Dey 2021). Recent studies of blockchain in agri-food authentication are listed in Table 2.

Monitoring the environment parameters and the fruit physiological status plays a vital role in fruit authentication for FFSC (Huang et al. 2023). Most fruits are harvested from living plants and maintain active metabolism to sustain biological integrity of the edible tissue (Mittler et al. 2022). Although ICT can ensure real-time communication, the processes of fruit cultivation, harvest, processing, storage, and logistics still need to be completed offline. In this complex and long commercialization process, the fruit quality tends to degrade rapidly (Zhang and Jiang 2019), negatively affecting the consumers' acceptability (Zhang et al. 2023; Zhang et al. 2023). To this end, Dong et al. (2021) studied ICT and blockchain-driven agricultural cross-channel information strategies and analyzed the relationship between pricing and behavior. Their results proved that retailers tended to leverage this strategy to complete more transaction when the devaluation coefficient of agri-food was low. Therefore, the evaluation of fruit sensory, biochemical, physical, and chemical indicators cannot be ignored. The traditional FFSC can hardly monitor the external environment, nor can it guarantee data security. With the help of blockchain,

the external environment of fruits can be monitored, analyzed, and certificated. Managers can adjust deteriorated environmental conditions in time. For example, Wang et al. (2021a) designed an alliance blockchain framework to identify agri-food through quick response (QR) codes and smart contracts, the program has already been proved to have the potential for commercial use. Farmers recorded details about the environment and crop growth data in the inter planetary file system (IPFS) and stored file hash values in smart contract, which not only increased data authenticity and security from hacking attacks or equipment failures, but rather alleviated the problem of central database storage explosion. In another insightful study of Saurabh and Dey (2021), the automated transaction based on IoT was proposed, in which the sensors were used to monitor grape quality and shelf stock units of wholesalers, thereby optimizing the pricing strategies, and eliminating inventory replenishment time.

In terms of decentralization, transparent and intelligent transactions, the blockchain network structure based on P2P has many advantages (Li et al. 2018). The first is openness, which eliminates restrictions of websites' access for participants which improves food transparency and authentication. In fact, almost all consumer believes that the transparency available of fruit processes is critical. They need to grasp fruit entire supply cycle to ensure the food safety, authenticity, and high quality (Astill et al. 2019). Secondly, the P2P digital interface can help FFSC to manage various complex operations, such as adding, deleting, modifying, and searching, etc. (Casey and Wong 2017). For instance, Baralla et al. (2021) designed a blockchain system for Sardinia, Italy to track the local agri-food in cold chain. The platform could monitor fruits information such as storage temperature, environment humidity, and global positioning system data (GPS) as the system is interfaced with IoT network devices. Moreover, the smart contract could guarantee the transparency and authenticity of food information. As for smart contract, which is an automated protocol based on blockchain technology that can autonomously execute contractual terms when predefined conditions are met, without third-party intervention (Puthenveetil and Sappati 2024). By embedding contractual logic into the blockchain through code, it ensures transparency, tamper-resistance, and efficiency in execution. Smart contracts are fundamentally reshaping commercial trust mechanisms. In this process, the transaction was digitally uploaded, and the company could read the record in real-time and optimize supply efficiency, including: (1) adjusting sale strategies according to the updated fruit freshness; (2) controlling the food-borne pollution and reducing fruit decay; (3) obtaining people's needs directly, thereby eliminating the bull-whip effect (rising supply costs caused by intermediate nodes) for decision-makers (Lu et al. 2021; Zhang et al. 2022a). Similarly, Liu et al. (2020) used big data to propose a more suitable supply chain of cost-sharing and revenue-sharing contract. From another angle, the blockchain could manage the information of FFSC, enhancing trust relationships and consumer loyalty, thus making it possible for the trust-lacking transaction model (Kamilaris et al. 2019). Therefore, potential high-quality fruit suppliers/consumers will be matched directly (Mao et al. 2019). Besides, P2P allows consumers to verify randomly and evaluate anonymously on producers/processors which exempts the third-party intervention (Nakamoto 2008). The best

TABLE 2 | Recent studies of blockchain in agri-food authentication.

Fields and purpose	Technologies	Main work and findings	References
Monitoring, authentication, and traceability of the entire agri-food supply chain. Build a multi-role, multi-link, multi-region food monitoring and transaction management system to improve the authentication of agri-food.	Blockchain, IoT, RFID, WSN, NFC, and ICT	Based on the blockchain architecture model, combining RFID, NFC, food identifiers, and wireless sensors to track, share, and certificate agri-food information; record the entire process of agricultural food planting, processing, and circulation through intelligent sensing equipment.	(Tian, 2016, 2017)
	Blockchain, tag, sensor, NFC, and smart contract	Used more private NFC to track and identify food; signed transactions for the blockchain by the tag.	Boehm et al. (2017)
	Blockchain, tag, sensor, and smart contract	Built a rice supply chain system in India using blockchain; assuring safety of rice from fraud, tampering, and falsifying information.	Kumar and Iyengar (2017)
	Blockchain, WSN, Ethereum, and QR code	Built a holographic database of the tea whole supply chain from farmland to table; adopted the food risk assessment and traceability technology based on the hazard factor.	Liao and Xu (2019)
	Blockchain, ICT	Constructed a theoretical analysis model to study ICT and BT-driven agricultural cross-channel information, strategies; analyzed the relationship between pricing strategies, and customer behavior.	Dong et al. (2021)
	Blockchain, IoT, WSN, cloud computing, and ML	Used IoT&ICT to automate transactions and auto-replenish product orders; identified potential drivers of blockchain adoption; employed a rating-based conjoint analysis in grape wine supply chain.	Saurabh and Dey (2021)
Decentralized, transparent, and intelligent transactions in the agri-food supply chain. Enhance the information security and blockchain storage capacity of the agricultural food supply chain, increase the trust value of the entire chain, reduce transaction fraud, and protect the interests of consumers.	Blockchain, smart contract, and QR code	Proposed a framework based on consortium blockchain and smart contracts to track and trace the workflow of agri-food supply chain; stored hashes in smart contracts; increased data security, alleviated blockchain storage explosion.	Wang et al. (2021a)
	Blockchain and big data	Investigated the convenience of E-agriculture based on blockchain in Chinese five villages.	Li, Wang and Li (2020)
	Blockchain, cloud storage	Used cloud storage to propose a blockchain-based encryption storage method and privacy protection scheme for agricultural monitoring data.	Liu, Huang and Wang (2021)
	Blockchain, IoT, fuzzy logic	Constructed a corrosive food traceability system via blockchain, IoT and fuzzy logic; established decision support by shelf-life adjustment and quality evaluation.	Tsang et al. (2019)
	Blockchain, big data, and sensing	Big data and blockchain improved the data security and transparency for	Wang (2019)

(Continues)

TABLE 2 | (Continued)

Fields and purpose	Technologies	Main work and findings	References
Information security and authenticity in the agri-food supply chain. Improve supply chain participation and broaden consumers' access to market, agriculture, and transaction-related information; improve blockchain throughput and reduce transaction delays.		private information; improved the speed of data collection and processing.	
	Blockchain, LM, SVM, and NB	Provided a blockchain-based credit evaluation system to supervise and enhance the food authentication.	Mao et al. (2018)
	Blockchain and big data	Revised the market demand function; built a revenue model with cost/benefit sharing.	Liu et al. (2020)
	Consortium blockchain, and smart contract	Proposed a system that allows nonprofessionals to design smart contracts according to their needs.	Mao et al. (2019)
	Public blockchain, and IoT	Created a virtual area based on the public chain to storage secure and immutable information.	Hammi et al. (2018)
	Public blockchain	Proposed an agri-food supply chain based on double blockchain architecture; studied the storage mode, resource rent-seeking, matching mechanism, and consensus algorithm.	Leng et al. (2018)
	Blockchain, linkable ring signature, and smart contract	Presented a new reputation evaluation system based on blockchain without a third party; protected user privacy.	Li et al. (2019b)
Sustainable agri-food supply chains. Increase the internal supply efficiency of the fresh fruit industry, realize the rationalization of resource allocation, reduce the economic, social, and environmental burden, and increase the possibility of sustainable development.	Blockchain and ICT	Relay-assisted wireless network transmission of sustainable E-agriculture information.	Song and Li (2021)
	Blockchain, technology assessment framework	Discussed the sustainable social and environmental impact of blockchain on the food supply chain via technology assessment framework.	Köhler and Pizzol. (2020)
	Blockchain, IoT, and big data	Proposed the combination of big data and blockchain to improve the sustainability of the food supply chain.	Zhang et al. (2020)
	Blockchain, smart contract, and GPS	Designed a blockchain system for tracking the local agri-food in cold chain; company could read the ledger in real-time and optimized supply efficiency.	Baralla et al., 2021
	Blockchain, IoT, and big data	The integration of IoT, big data and blockchain can create a data-driven sustainable agri-food supply chain.	Kamble, Gunasekaran and Sharma (2020)
	Blockchain, sensors	Designed a blockchain-based E-agriculture circular agriculture framework for ecological farm.	Chen Li and Li (2020)
	Blockchain, ML, and IoT	Evaluated the proposed framework <i>FarMarketplace</i> .	Leduc, Kubler and Georges (2021)
Other fields. Solve the detailed problems in the implementation of the blockchain;	Blockchain	Discussed mathematical models and food quality indexes to ensure that consumers were provided with quality food.	George et al. (2019)

(Continues)

TABLE 2 | (Continued)

Fields and purpose	Technologies	Main work and findings	References
optimize the business model; provide consumers with high-quality food, etc.	Blockchain, IoT, and ICT	Addressed interoperability issues between heterogeneous IoT-based services by offering a harmonized AIP.	Kitouni et al. (2018)
	Blockchain	Took 202 text related to blockchain and food safety on Chinese Zhihu platform via information adoption model.	Hong et al. (2021)

example on this issue was reported by Mao et al. (2018), in which the authors provided a blockchain-based credit evaluation system to supervise and enhance the food authentication for agri-food supply chain. The system gathered and analyzed credit evaluation text from traders by smart contracts and depth machine learning (LM) named long short-term memory (LSTM). The LSTM showed better performance than support vector machine (SVM) and naive bayes (NB) in the aspect of supervision for the transaction behavior.

With the continuous accumulation of fruit monitoring data, the space, authenticity, and privacy of local storage data have also become urgent issues which challenges farmers, governments, and consumers. Similarly, researchers also tirelessly search for the efficient solutions in this area for years. Hammi et al. (2018) created bubbles trust (virtual area) from public blockchain which ensured a robust identification and authentication of sensing devices, thus improving the security of private information. Li et al. (2019a) presented a new reputation evaluation system based on blockchain, in which the third party was removed, and the user privacy could be protected. Song and Li (2021) assessed relay-assisted wireless networks to meet the massive communication needs of rural areas. However, the exploration of this field in agri-food is still relatively lacking, and further exploration is needed in the future.

The blockchain helps to improve the sustainability of FFSC in economic, environmental, and social dimensions. Firstly, it reduces cumbersome audit steps from the third-party which decreases transaction costs greatly (Tönnissen and Teuteberg 2020). Y. Chen et al. (2020) proposed a circular E-agriculture framework based on blockchain for an ecological farm in Beijing from a sustainable perspective. The framework expanded the shared information set, thereby eliminating unreliable third agencies, as well as allowing retroactivity for organic food. The combination of blockchain and E-agriculture realized the self-management of agricultural equipment. The proposed model was especially suitable for unmanned farms, or those lacking effective management, which could greatly reduce postharvest waste of the fruits (Xu et al. 2017). Intriguingly, the study of Leduc et al. 2021 emphasized the importance of digitalized market design and templated smart contract trade. Then, the authors evaluated the proposed agricultural market framework based on blockchain (Far-Marketplace) and promoted a restrictive evaluation method for food blockchain system. In addition, blockchain strengthened the participation of the FFSC to realize win-win cooperation, maximizing benefits while

minimizing risks, leading to a sustainable FFSC (Kamilaris et al. 2019). For example, Kamilaris et al. 2019 suggested that the integration of IoT, big data, and blockchain could achieve a data-driven sustainable agri-food supply chain. The sustainability could improve ecology quality and food safety, further promoting consumer acceptance, presenting an unprecedented virtuous circle in food industry (Feng et al. 2020). Köhler and Pizzol (2020) also discussed the positive sustainability impact posed by blockchain on the authentication of the food supply chain via the application technology assessment framework.

In other food application scenarios of the integration of blockchain and E-agriculture, George et al. (2019) presented a restaurant model, discussing the relationship between the mathematical models and the food quality indexes (FQI), for providing high-quality food, technology standard, cost-effectiveness, and information security. Hong et al. (2021) studied 202 public text data related to blockchain and food safety on Chinese Zhihu application program based on the information adoption model, in which the four factors of advantages, costs, national policy, and supervision have significant effects on the public's recognition and adoption with a confidence level of 0.1. In addition, several studies also discussed the opportunities and challenges of blockchain application in the food industry, including the investment decisions, the acceptance of rural people, among others (Kamilaris et al. 2019; Liu et al. 2020).

4 | The Technology Evaluation and Application Barriers

The implementation of IoT technologies has obvious advantages for FFSC (Liu et al. 2020). Nevertheless, assessing the pros and cons of the technical framework cannot be ignored.

Sensors can monitor the environment parameters which ensures the authentication of fruit information, maintains timely communication in whole supply chain, improving the efficiency of FFSC services. Albeit the construction of sensing devices in cold chain is difficult owing to the remote and scattered distributed orchards. The existing logistics system also cannot solve the problem of "first & last kilometer" in delivery (Hong et al. 2021; Huang et al. 2023). Consequently, the absent of internet especially in remote areas can hinder data transmission of sensing devices in fruit origins. In addition, the current study

mainly focuses on data storage and analysis, ignoring the standardization of data collection for sensors (Bai et al. 2021).

The mathematical coupling models of fruit can provide early decay warning, which reduces the rot loss of FFSC. Most studies only consider the decay degree and freshness of fruit (Zhang et al. 2022a; Huang et al. 2023), with needed studies to optimize the model to integrate fruit sensory and nutrients (poly-saccharides, polyphenols, flavonoids, alkaloids, etc.). It is worth noting that the model requires reliable preliminary experimental data to estimate parameters and it needs to be updated continuously since different varieties, origins, or seasons.

With the development of cryptography and mathematical calculations, vulnerabilities of blockchain asymmetric encryption become increasingly prominent, causing difficulty to balance the information transparency and privacy protection for the FFSC (Anithaashri and Baskaran, 2016). For example, tampering of original data, “51% attacks”, loss of private key and incorrectly coded smart contracts will directly lead to illegal transactions and leads to huge loss of resources (Xu et al. 2022). The “51%” is the most typical form of systemic risk. When an attacker controls more than 50% of the network’s computational power or staked tokens, they gain dominant control over new block generation and transaction validation, which may lead to a breakdown of the underlying consensus mechanism of the blockchain. The current smart contracts are still in the screening stage for degraded fruits, with a lot of space for further development of the compatibility of computer languages. On the other hand, the exponentially increasing historical data brings trouble in storage space and transaction delay (Liu et al. 2020), imposing great restriction on high-frequency small-scale fruit transactions. Additionally, more convenient, and intuitive fresh fruit trading application program for individual should be developed to meet different needs. The FFSC involves multiple interests in economic and social area. The IoT framework requires close coordination and cooperation between participants to achieve efficient operations. This process will break the fixed interest relationship, leading to social issues such as secondary distribution and unemployment (Köhler and Pizzol 2020; Xu et al. 2017). Secondly, the regulatory differences and legal applicability of smart blockchain need to be paid special attention, especially in fruit trade involved in cross-border. Thirdly, the blockchain virtual tokens may bring the risk of bubble economy. Other sustainability issues are also nonnegligible such as huge maintenance costs for blockchain and the power waste of proof of work (PoW) computing (Li, Barenji and Huang 2018; Kitouni et al. 2018).

5 | Conclusions

In recent years, agri-food fraud has led to a loss of food safety and reduced public trust in food supply chain, especially for fresh fruit which has undergone only primary processing. In the process of circulation, storage, and processing, the quality of postharvest fruit gradually degrades or even rots. Therefore, fruit information authentication, supply chain transparency and data storage security have been the key issues in the field of food safety. To this end, it is necessary to apply emerging

technologies into the FFSC. The IoT technologies is an effective strategy for enhancing food authentication. This study reviews the latest applications of IoT technologies in FFSC, highlighting their potential to authenticate fruit true information, predict fruit shelf-life, and improve supply chain efficiency. The technical evaluation and application obstacle analysis are also carried out. As a result of the present work, gas sensors and RFID can collect and transmit environmental parameters throughout the FFSC from fruit cultivation to consumption. The mathematical coupling model in remote monitoring database is used for fruit quality simulation and shelf-life prediction. In addition, the optical sensing technology can also be used for fruit authentication which greatly limits substitution and counterfeiting incidences. Finally, the fruit supply process and transaction information are distributed and encrypted via the blockchain, creating a secure and permanent record. These emerging technologies have promoted the development of the fruit trading market in a sustainable direction. Although IoT technology offers significant potential for comprehensive service improvement in FFSC, its implementation in developing countries or small-scale farms may face limitations due to inadequate infrastructure, limited financial resources, etc.

Author Contributions

Yiqin Zhang: conceptualization, investigation, writing – original draft. **Simin Fan:** writing – original draft, methodology, data curation. **Ruiling Liu:** methodology, resources, investigation. **Huizhi Chen:** conceptualization, investigation. **Ben Niu:** methodology. **Hangjun Chen:** methodology, resources, supervision, writing – review and editing. **Weijie Wu:** writing – review and editing, resources, supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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