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Internet of battery-free sensing for food monitoring

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ABSTRACT

Food quality and safety are very important in our daily lives. The food supply chain is very complex, and the transparency, traceability, and sustainability of the food in the supply chain must be improved further by quality monitoring in real-time. However, the food themselves have biological liveliness, and the traditional rigid internet of smart sensing systems has issues such as inflexibility in deployment, low biological adaptability, high energy consumption, low device fabrication efficiency, and high cost for food organisms and systems. Their normal operation requires additional battery energy for power supply. Once the energy is depleted, the process of food quality monitoring will be forced to be interrupted and unsustainable. Therefore, developing a battery-free wireless sensing network for food monitoring would have the potential to increase the innovative development of food quality.

KEYWORDS

Internet of battery-free sensing; Food monitoring; Food quality and safety; Food supply chain

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Introduction

Smart sensing is one of the important fundamental technologies for guaranteeing food quality and safety in the supply chain. The food supply chain is very complex since it has various stages that include planting/breeding, harvesting, processing, storage, circulation, and sales. The complexity, information asymmetry, and environmental coupling between each stage in the supply chain could easily lead to uncertainty, opacity, untraceability, and a high loss of food quality. The internet of smart sensing for food monitoring, such as the wireless sensor network, is critical to solving these problems. However, the food themselves have biological liveliness, and the traditional rigid internet of smart sensing systems has issues such as inflexibility in deployment, low biological adaptability, high energy consumption, low device fabrication efficiency, and high cost for food organisms and systems. Moreover, their normal operation requires additional battery energy for power supply. Once the energy is depleted, the process of food quality monitoring will be forced to be interrupted and unsustainable. The large batteries used in the traditional Internet of smart sensing would be a great challenge in the actual food supply chain. Ultimately, it leads to issues such as food quality traceability chain breakage and an increase in quality loss rate.

Internet of battery-free sensing (IoB) could achieve more flexible, easier to deploy, and more reliable battery-free acquisition, transmission, and processing of sensing signals than traditional battery-powered sensing systems for food monitoring by combining flexible electronic circuit and dynamic wireless radio frequency identification (RFID) technologies (Figure 1). Battery-free sensing technologies would undergo maturation with more flexible, biocompatible, and sustainable, and more quality sensors could be developed and integrated into the battery-free sensing tags to directly monitor the food quality without building complex models. However, it would take a long time to fully realize an actual food supply chain. Therefore, a vision of the future of IoB and the challenges on the implementation route in the food supply chain are discussed.

Sensing Micro-Environmental Parameters

Food quality is strongly affected by the micro-environmental parameters in the supply chain. The micro-environmental parameters mainly include the temperature, humidity, gases and microbe [1]. The temperature is the most important parameter to keep the food quality in the supply chain, especially in the food cold chain. The low temperature should be kept at a stable status when the food is in the process of storage and refrigeration transportation. The humidity could provide a stable high humidity for fresh fruits and vegetables. The gases could be used to modify the atmosphere of fresh food to ensure their quality. The microbes still exist all the time during the whole process of the food supply chain. It is an important indicator to indicate the quality of pollution in the supply chain. There are many kinds of sensor technologies that could be used for realizing the sensing of the micro-environmental parameters, such as resistive sensing, electrochemical sensing, and bio-sensing techniques. However, most of them are made up of hard-printed circuit boards, and they also need extra batteries for power. How to realize their flexible and battery-free sensing in real-time still remains challenging.

Sensing Quality Parameters

Quality parameters could directly indicate the food quality in supply chain [2]. The texture could indicate the food physical properties of the fruit, vegetables, and meat, such as firmness, toughness, chewiness, resilience, etc. The freshness could be indicated by the color, smell and sensory. The total bacterial colony count (CFU) is the total number of bacterial colonies grown per gram (per milliliter) of the measurement sample under certain conditions, such as aerobic conditions, nutritional conditions, pH, culture temperature time, and so on [3]. It is usually applied to indicate the meat and fish in the supply chain to directly monitor their quality. The volatile base nitrogen (TVBN) refers to the alkaline nitrogen-containing substances such as ammonia and amines produced during the

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spoilage process of animal foods due to the action of enzymes and bacteria [4]. This type of substance is volatile, and the higher its content, the more amino acids are destroyed, especially methionine and tyrosine, thus greatly affecting its nutritional value. Therefore, the content of TVBN could be used to directly determine the freshness of animal food such as meat and fish. The quality parameters are very important for food quality monitoring in the supply chain. However, the samples of these quality parameters need to be determined offline. They could not directly be determined by the sensing system in real-time during the whole supply chain. The quality parameters sensors would be another challenge for directly monitoring the food quality in real-time in the supply chain. Then, the battery-free quality sensing would further be realized with more flexibility, low cost, and sustainability.

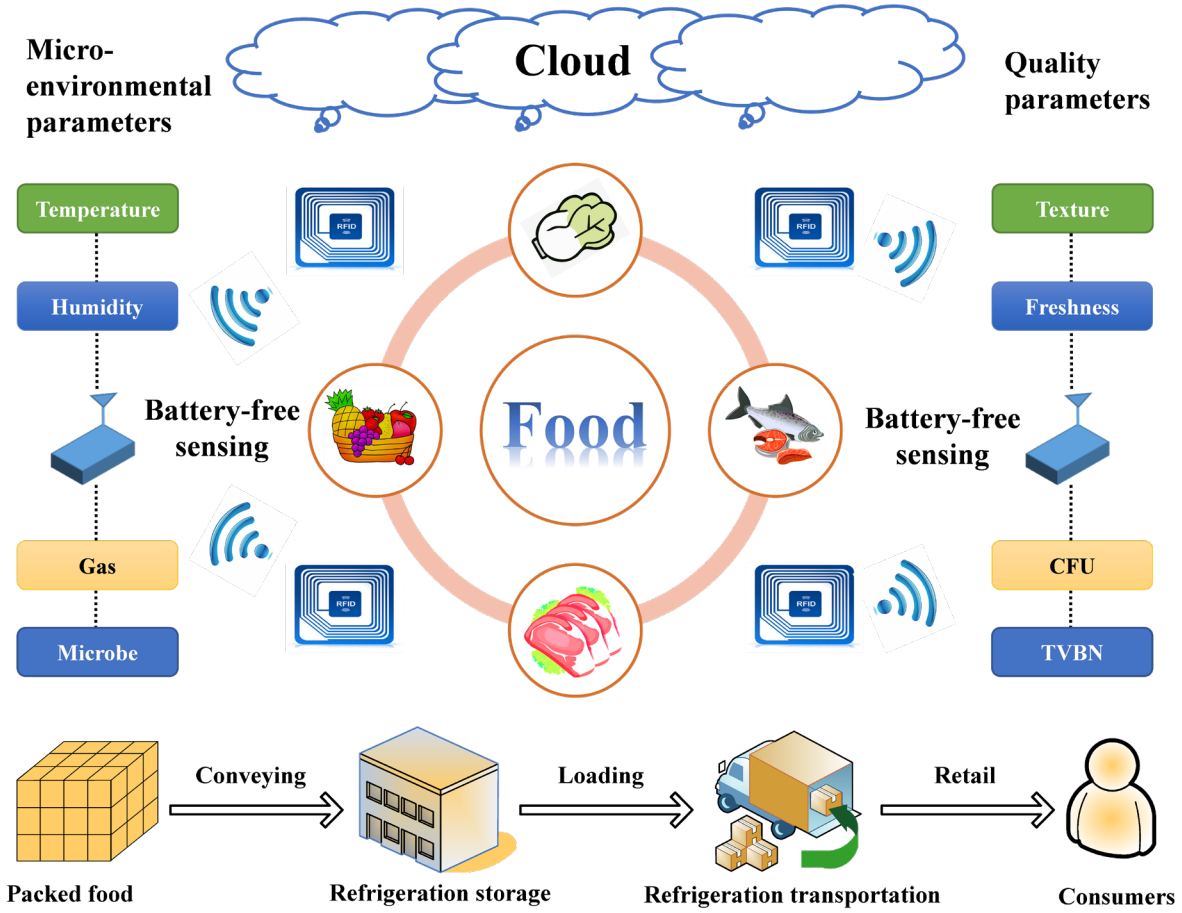

Figure 1. Envisioned architecture for Internet of battery-free sensing. Micro-environmental battery-free sensors, quality parameters, and dedicated electronics are distributed throughout the food supply chain and wirelessly transmitted to the cloud center.

Battery-Free Wireless Sensing Network

The battery-free wireless sensing network includes the battery-free sensing tags, the wireless reader, the aggregation node, and the cloud center. Ideally, the battery-free sensing tags could integrate the micro-environmental and food quality sensors with the RFID technologies [5]. The tags could be easier to realize in situ or wearable sensing by fabricating with flexible, biocompatible materials. The wireless reader could wirelessly acquire the battery-free sensing data in real-time by RFID. The aggregation node could aggregate the sensing data from the wireless reader and then communicate with the cloud center. The cloud center could trace and manage all the micro-environment and quality information of the food and make decisions based on the real-time data, for example, the micro-environmental parameters control, the quality chain breakage warning, the traceability of food quality, and so on. The models between micro-environmental and quality parameters would also be built in the cloud center using advanced neural networks, machine learning methods, and so on. The energy, such as solar and wind outdoors, could be harvested as the power for the wireless reader and aggregation node to realize the self-powered, sustainable, battery-free wireless sensing system for food monitoring in the supply chain [6]. Currently, most of the advanced materials, flexible electronics, energy harvesting, and wireless sensing technologies offer the most favorable conditions for implementing such battery-free wireless sensing networks.

IoB Implementation

To realize the IoB for food monitoring in the actual supply chain, sensors are one necessary and important aspect; another important aspect is the model between the micro-environmental and quality because of the off-line quality

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parameters determination in actual situations. The battery-free sensors could be expanded not only the temperature, humidity, gas and microbe, but also the advanced sensor technologies such as the optical sensors. To build the models, the advanced neural network, artificial intelligence (AI), and machine learning methods such as deep learning and convolutional neural networks could be applied for the data training and model construction based on the real-time sensing data and quality parameters [7]. The big and difficult challenge is how to improve the accuracy of the models. The big data from the sensors and quality are needed. Therefore, comprehensive studies using battery-free wireless sensing networks and advanced models such as advanced neural networks, deep learning, and machine learning models are needed.

After the implementation of the IoB, how to use the sensing data to monitor and control food quality in the supply chain with low cost and sustainability. This question could be addressed through direct quality sensing in further the models and also the decision control strategy in the cloud center. The answers to these questions will depend on food quality determination methods, battery-free sensing cost, and type, and also on the control parameters for food quality conditions in the supply chain.

Conclusions

With the rapid development of the advanced flexible sensor, battery-free sensing, AI, and biotechnologies, the IoB would have a great potential for implementation in the actual supply chain to guarantee food quality and safety. Battery-free sensing technologies would undergo maturation with more flexible, biocompatible and sustainable, and more quality sensors could be developed and integrated into the battery-free sensing tags to directly monitor the food quality without build the complex models. The sensor parameters would also be expanded with more types, such as biosensors, optical sensors, chemical sensors, and so on. Since battery-free sensing has a limitation in energy harvesting, the extra energy harvesting technologies could be combined. As many low-cost energy harvesting technologies have been proposed, such as photoelectric generation, thermoelectric generation, piezoelectric generation, and triboelectric nanogenerator, etc., fully self-powered battery-free sensing would be possible to realize the sustainable monitoring of the food quality in the supply chain. Ultimately, by combining the AI models, these advancements would result in smart, sustainable, flexible, self-powered, battery-free sensing and control solutions tailored to user needs. The IoB would substantially increase the adoption of battery-free sensing for food monitoring, ensuring the transparency, traceability, and sustainability of food quality and safety in the actual supply chain.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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