Application of Smart Sensors and IoT in Processing and Quality Monitoring of Functional Foods

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Abstract

The increasing demand for functional foods and nutraceuticals has necessitated the development of advanced technologies to ensure product quality, safety, and nutritional stability. Functional foods, enriched with bioactive compounds such as probiotics, antioxidants, vitamins, and minerals, are highly sensitive to processing conditions. Conventional quality monitoring techniques are often limited by delayed analysis, lack of real-time data, and reduced accuracy. In recent years, smart sensors and Internet of Things (IoT)-based systems have emerged as transformative tools in food processing industries. These technologies enable continuous, real-time monitoring of critical parameters such as temperature, humidity, pH, gas composition, and microbial activity. The integration of IoT platforms allows seamless data acquisition, storage, and analysis, facilitating automated decision-making and predictive quality control. Furthermore, the incorporation of machine learning algorithms enhances the capability of these systems to predict shelf life, detect spoilage, and optimize processing conditions. This explores the applications of smart sensors and IoT in functional food processing, focusing on their role in quality monitoring, process optimization, and shelf-life prediction. The challenges and future prospects of these technologies in developing intelligent and sustainable food systems are also discussed.

Keywords: Bioactive compounds; Real-time monitoring; Machine learning; Shelf-life prediction; Process optimization

1. Introduction

Functional foods are defined as foods that provide health benefits beyond basic nutrition due to the presence of biologically active components. These include probiotics, prebiotics, dietary fibers, antioxidants, and bioactive peptides. The global demand for functional foods has significantly increased due to growing consumer awareness regarding health and wellness. However, the processing of functional foods presents unique challenges. Bioactive compounds are highly sensitive to environmental conditions such as temperature, oxygen, light, and pH. Even slight variations during processing or storage can lead to degradation of these compounds, thereby reducing the nutritional and functional value of the product (Arshad et al., 2025).

Laboratory-based chemical analysis serves as a traditional quality monitoring method which requires extensive time and fails to deliver immediate results. Food processing companies now use advanced technologies because of this limitation which makes traditional monitoring methods unworkable. Smart sensors possess the ability to detect and measure physical and chemical and biological parameters with their advanced measurement capabilities. IoT systems benefit from these sensors which provide live data acquisition and distant monitoring and system process control capabilities (Rafiq et al., 2024). The combination of these technologies establishes the basic structure for intelligent food processing systems which people commonly call Food Industry 4.0.

2. Functional Foods and Their Processing Requirements

2.1 Definition and Scope

Functional foods encompass a wide range of products, including probiotic dairy products such as yogurt and kefir, fortified beverages, nutrient-enriched cereals, and bioactive-rich plant extracts. These foods provide health benefits which extend beyond essential nutrition by improving gut health and boosting antioxidant defenses and increasing nutrient absorption capacities (Frumuzachi et al., 2025). The processing and storage of bioactive components face major difficulties because their active properties and essential functions become unstable through exposure to different physicochemical stress conditions.

2.2 Processing Challenges

The processing of functional foods is highly complex, as bioactive ingredients are often susceptible to degradation under unfavorable conditions such as high temperatures and oxidative environments and extreme pH levels. Probiotics require strictly controlled fermentation conditions which include optimal temperature and pH to maintain their viability and functional efficacy. The thermal processing and oxidation used in fortified beverages lead to higher losses of nutritional quality and lower bioavailability of vitamins and phytochemicals present in the product. The manufacturing process of nutrient-enriched cereals requires complete moisture control during extrusion and drying operations because any moisture variation will lead to nutrient loss and product texture and structural integrity destruction. Plant-derived antioxidants which include polyphenols face oxidation when they come into contact with both light and oxygen, which leads to decreased functional properties. Biochemical compounds in functional foods need to be preserved through proper processing methods that enable sensory quality maintenance which determines product acceptability and effectiveness (Pramanik et al., 2023).

3. Smart Sensors in Food Processing

3.1 What Are Smart Sensors?

Smart sensors function as devices which detect physical and chemical and biological parameters and transform those measurements into digital signals which enable monitoring and control. Smart sensors play an essential role in food processing because they deliver constant real time data which protects product quality and safety (Rajak et al., 2023).

3.2 Types and Applications

- **Temperature sensors** - ensure optimal heat profiles in fermentation, drying, and cold chain storage.
- **Humidity sensors** - regulate moisture to prevent spoilage and microbial growth.
- **pH sensors** - crucial for fermentation-based products (e.g., probiotic dairy) to maintain acidity levels.
- **Gas sensors (O_2, CO_2)** - used in packaging to detect oxidation and spoilage events.
- **Biosensors** - enable rapid detection of pathogens and contaminants, enhancing food safety.

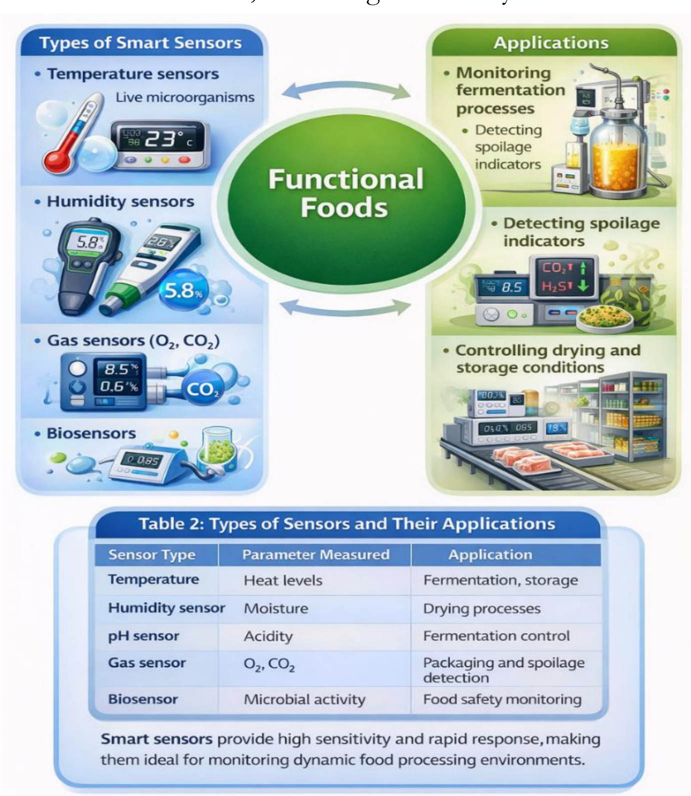

Table 2: Types of Sensors and Their Applications

Sensor Type	Parameter Measured	Application
Temperature	Heat levels	Fermentation, storage
Humidity sensor	Moisture	Drying processes
pH sensor	Acidity	Fermentation control
Gas sensor	O_2, CO_2	Packaging and spoilage detection
Biosensor	Microbial activity	Food safety monitoring

Smart sensors provide high sensitivity and rapid response, making them ideal for monitoring dynamic food processing environments.

Fig. 2. Smart sensors in food processing illustrating sensor types, measured parameters, and applications

Recent advances in gaseous sensor technologies are improving limits of detection for spoilage indicators, thereby enhancing safety and quality monitoring. Smart sensors are not only used for parameter monitoring but also for digital traceability and predictive analytics when integrated with data platforms.

4. Internet of Things (IoT) in Food Processing

4.1 The IoT Concept

The Internet of Things (IoT) connects physical devices that have sensors and communication modules and processing units to create a system for data collection and transmission and network-based data analysis. The food processing industry uses IoT technology to achieve immediate equipment and storage facility and supply chain monitoring through its ability to track assets in real time (Choudhary et al., 2025). The combination of IoT technology with Industry 4.0 systems functions as the primary mechanism which enables food production plants to develop advanced manufacturing capabilities with enhanced operational flexibility.

4.2 Key Features and Benefits

IoT systems in food processing support:

- Real-time condition monitoring
- Remote access and control via cloud platforms
- Automated alerts
- Data storage and predictive analytics

Applications extend to cold chain monitoring, inventory management, supply chain traceability, and automated quality control systems. For instance, IoT frameworks integrated with biosensors can detect food quality deterioration in packaging and cold storage, significantly improving product safety and reducing waste.

5. Integration of Smart Sensors and IoT in Functional Food Processing

5.1 System Integration and Process Control

Intelligent food processing systems which use smart sensors together with IoT technology enable real-time monitoring and automated control functions. The processing of functional foods requires this integration because bioactive compounds react to environmental changes. The system provides constant monitoring of temperature and pH and moisture and gas levels which operators can modify as needed. The system achieves better process management because it decreases human mistakes and maintains product quality and preserves nutrients. The system uses temperature and pH sensors to track probiotic fermentation because they show whether microbes are alive. IoT-based systems enable proper storage management which helps keep bioactive compounds intact.

5.2 IoT + Machine Learning Applications

Machine learning (ML) algorithms can analyse large datasets generated from IoT systems to derive actionable insights such as:

- **Shelf-life prediction** - estimating expiry based on environmental history.
- **Quality grading** - using sensor fusion and pattern recognition.
- **Spoilage detection** - early warning systems for microbial or oxidative events.

These data-driven methods improve operational reliability, reduce product loss, and enable predictive quality control.

Table 1: Integration of Smart Sensors, IoT, and Machine Learning in Food Processing

Parameter	Technology Used	Role	Benefit
Temperature control	Sensors + IoT	Real-time monitoring	Maintains product stability
Fermentation control	pH sensor + IoT	Continuous data tracking	Ensures microbial viability
Packaging monitoring	Gas sensor + IoT	Oxygen level detection	Prevents oxidation
Shelf-life prediction	Machine Learning	Data analysis	Expiry estimation
Quality grading	ML + Sensor data	Pattern recognition	Product classification

6. Machine Learning for Shelf-Life Prediction and Quality Grading

The process of machine learning (ML) enables modern food quality monitoring because it processes extensive complex data sets which stem from IoT sensor networks and imaging systems and food processing machinery. Machine learning (ML) enables food systems to achieve accurate decision-making through its ability to discover concealed patterns which link environmental factors and processing conditions and product responses (Liakos et al., 2025).ML algorithms such as supervised learning (e.g., regression, support vector machines, random forests) and deep learning models (e.g., convolutional neural networks) are widely applied for the following purposes:

- **Shelf-life prediction** – ML models integrate data from temperature, relative humidity, gas composition (O_2, CO_2, ethylene), and storage conditions to predict product deterioration kinetics and estimate remaining shelf life with high accuracy. Dynamic models can also adapt to real-time changes in the supply chain.
- **Quality grading** – Image-based ML techniques combined with computer vision enable automated classification of food products based on size, shape, color, texture, and surface defects. This ensures consistent grading standards and reduces human subjectivity in sorting operations.
- **Spoilage detection** – ML models utilize sensor data (electronic nose, electronic tongue, NIR spectroscopy, hyperspectral imaging) to detect early biochemical and microbial changes, enabling rapid identification of spoilage before it becomes visible or unsafe.
- **Anomaly detection** – Advanced ML systems can identify deviations from normal storage or processing conditions, providing early warnings for contamination, equipment failure, or improper handling.
- **Process optimization** – ML helps in optimizing processing parameters (e.g., drying, fermentation, storage) by correlating them with final product quality, thereby improving efficiency and consistency.
- **Supply chain intelligence** – Integration of ML with IoT allows prediction of quality loss during transportation and storage, enabling better logistics planning and reduced post-harvest losses.

ML-driven systems enhance operational efficiency, minimize food waste, support intelligent automation, and ensure consistent product quality and safety. The integration of ML with IoT, cloud computing, and advanced sensing technologies represents a key advancement toward smart food processing and Industry 4.0 applications in the food sector.

8. Conclusion

Integrating smart sensors and IoT technologies into functional food processing allows real-time monitoring, data-informed decision-making, and automated control, addressing limitations of traditional methods. While challenges such as cost, data security, and standardization remain, continued research advancements in sensor design, connectivity, artificial intelligence, and analytics are expected to accelerate adoption. These data-driven, intelligent systems will be foundational for high-quality, safe, and functional food production in the era of Industry 4.0 and beyond.

9. References

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