

IoT Enabled Smart Packaging System for Food Safety and Quality Control: A Systematic Review

Author Name & Affiliations

Ishita Priya Menon

Department of Computer
Science Missouri University
of Science and Technology
ishitamemon@mst.edu

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Abstract

The way we package food is changing fast. Old ways of packaging food are moving toward systems because of the Internet of Things (IoT). This review looks at how Internet of Things (smart packaging helps keep food safe and good to eat while it moves through the supply chain. I looked at different tools, like sensors that track things smartphone tools that use light and cloud systems that use machine learning. This paper brings together everything we know about sensors, networks and how people use them. I also looked at how we track gas, temperature and humidity. These tools range from NodeMCU setups to special arrays, for vacuum-packed food. I also looked at how computers can sort this data. Finally this review shows how well these systems work and talks about what we need to do in smart agriculture logistics.

INTRODUCTION

Critical barriers exist with respect to perishability, environmental sensitivity, and contamination issues that confront the global food supply chain system, thus making the conventional inspection system redundant. Contamination issues in the past have highlighted the importance of traceability of the entire supply chain from an economic perspective and from a health perspective [1]. While traditional packaging acts as a static barrier, smart packaging systems interact with the internal atmosphere [2].

The smart packaging system can be classified into two categories, data carriers (e.g., bar codes, RFID), and packaging indicators (gas, time-temperature, and chemical sensors). The integration of these elements in IoT enables real-time ubiquitous data sharing such that the consumers and logistics managers are able to constantly monitor the quality of products [4]. In this paper, we give an overview of current approaches combining low cost physical sensors, computer vision, and machine learning models to protect the quality of food.

signals of skills. The built-in design considers free text responses by workers as a valuable analytical input alongside structured survey questions.

ARCHITECTURAL FRAMEWORK OF IOT IN SMART PACKAGING

The incorporation of technical elements into the IoT food surveillance pipeline follows a traditional architecture of three layers [5].

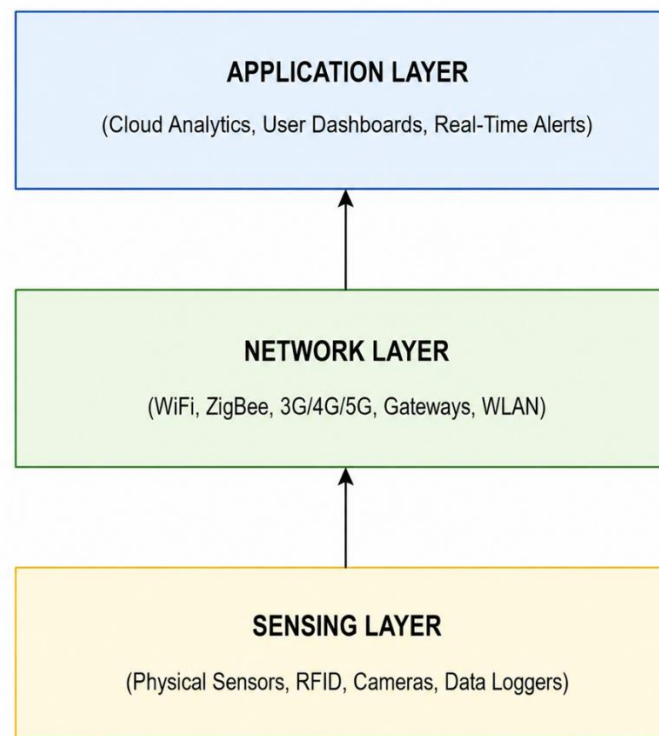


Fig 1: IoT packaging

SENSING LAYER

The sensing layer is responsible for the acquisition of physical information and short-distance cooperation. Environmental irregularities are detected through the use of hardware elements including physical transducers, high resolution cameras, and RFID systems [6]. The short-distance interaction protocols include Wireless Sensor Network (WSN), near field communication (NFC), and dedicated middleware [7].

NETWORK LAYER

As a means of communication between the nodes, the network layer is responsible for the transfer of telemetry data from the sensing nodes to the core storage cluster [8]. The network layer is comprised of various forms of technologies like 2.5G/3G/4G, GPS, WLAN, Bluetooth, and local hardware gateways [9].

APPLICATION LAYER

Long-term data storage, semantic integration, and dashboard display are performed by the application layer [10]. This is done using a service support layer that has cloud computing platform and peer-to-peer P2P architecture to cope with high traffic volumes [11]. Human-machine interaction is provided through the last service layer.

SMART INDICATORS AND SENSING MODALITIES

CHEMICAL AND VISUAL PACKAGE INDICATORS

- Package indicators constantly send signals concerning freshness through internal chemical changes:
- Fadable Inks: Labels printed with oxygen-sensitive ink compositions change color or disappear over time according to cumulative temperature exposure [12].
- Polyaniline (PANI) Films: Function as active chemical gas sensors that change color when exposed to basic byproducts like ammonia released during bacterial fish spoilage.
- Cellulose Membrane Stickers: Colorimetric indicator tags utilizing immobilized methyl red on bacterial cellulose can sense chicken decomposition; the tag transitions from red to yellow as volatile amines increase the package headspace pH.

DIRECT GAS AND ELECTROCHEMICAL TRANSDUCERS

Gas production through decomposition is measured by placing several sensor modules within storage containers. Measurement of methane (CH₄) gases, which are commonly produced during decomposition, is efficiently performed by means of SnO₂ semiconductor film used in gas sensors, including the MQ4 module [13]. Modern solutions, such as MQ5 or Bosch BME680, include measurements of carbon monoxide (CO)

gases, various VOCs, and volatile alcohols in order to identify early decomposition of vegetable products, including onions [14].

Sensor Module	Targeted Analytes / Variables	Primary Application Environment	Source
DHT11 / DHT22	Temperature & Relative Humidity	Storage environment and micro-controller enclosure health	
MQ4	Methane Gas (CH_4), 300 to 10,000 ppm	Domestic and commercial food decomposition tracking	
MQ5	LPG, CH_4 , H_2 , Alcohol, CO	Chemical signature mapping for vacuum-sealed foods	
BME680	Gas, Temperature, Atmospheric Pressure, Humidity	Integrated multi-parametric vacuum packaging analysis	

DATA ACQUISITION, PROCESSING, AND PREDICTIVE MODELING

HARDWARE INTEGRATION PROTOCOLS

Current-day monitoring nodes utilize low power microcontroller units such as NodeMCU ESP8266 and Arduino Mega 2560 [15]. These microcontrollers interact with the sensor arrays through serial buses such as I2C and SPI interfaces. Microcontrollers continuously sense the variations in voltage across the resistance (RL). This gives a digital value in terms of ppm [16].

SENSOR CALIBRATION ALGORITHMS

Electrochemical gas sensors must be stabilized by following systematic procedures because of the sensitivity of the sensors to various gases and baseline drifts. For example, to calibrate the MQ5 sensor, a graph of the baseline resistance (RSCA) against load characteristic is needed to determine the reference resistance (R0). Internal resistance (Rs) of the sensor can be determined using:

$$R_S = R_L \frac{V_s - V_{out}}{V_{out}}$$

The automation is configured to have a warm-up wait algorithm that consistently polls the reference data until the difference between two consecutive minutes becomes stable:

$$|\Delta R_0[n]| = |R_0[n] - R_0[n - 1]| < 0.5 \Omega$$

With the above condition fulfilled, the software will convert the active voltage values into the ppm concentration values of the target compound via:

$$\log(ppm) = \log a + b \log \left(\frac{R_s}{R_0} \right)$$

MACHINE LEARNING AND IMAGE PROCESSING FRAMEWORKS

While the physical gas sensor technique helps measure food quality based on the emitted odor, computer vision pipelines enable grading of food items using their visual appearance. High-resolution photographs of food are taken and fed into a machine learning process:

- i. Image Segmentation: Region of interest (ROI) is identified from dynamic noise of the background using K-means clustering algorithm, whereby clustering is performed based on squared Euclidean distance patterns in localized form.
- ii. Feature Extraction: PCA eliminates the redundant elements of the images while keeping only the significant feature vectors that describe color, texture or structural imperfections.
- iii. Classification: The trained statistical models then assess the profile of the images produced from the data set. The classification is done using machine learning techniques such as the K-Nearest Neighbor, Naive Bayes, and COA-SVM.

The mathematical efficiency of these predictive models is validated through standard statistical metrics:

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN}$$

$$\text{Sensitivity} = \frac{TP}{TP + FN}$$

$$\text{Specificity} = \frac{TN}{TN + FP}$$

SYSTEMS IMPLEMENTATION AND CASE STUDIES

OPEN-SOURCE CLOUD TELEMETRY IMPLEMENTATIONS

Affordable solutions involve the integration of a NodeMCU microcontroller with sensors like DHT11 and MQ4 to provide atmospheric telemetry feeds straight into free IoT data centers including ThingSpeak. This involves the use of conditional automation applications such as IFTTT (If This Then That) to check for any threshold. When there is excess heat or methane in storage, cloud alerts are initiated or fans switched on.

VACUUM-SEALED ATMOSPHERE TRACKING

- Vacuum food research has been conducted on the behavior of such foods using internal sensor networks. Using slices of onions (*Allium cepa*) with the integration of BME680/MQ5 system, the dynamics of low-pressure food storage can be seen:
- Atmospheric Pressure: Under conditions where air is removed to produce low vacuum pressure (around 600 hPa), the absence of oxygen reduces the rate of respiration metabolism in plants.
- Moisture Dynamics: The internal package relative humidity increases by about 30 percent at the onset of packaging to reach an equilibrium state. This indicates that at the onset of packaging, moisture vapor is emitted from the cut cells of the plant.
- Exothermic Enzyme Signatures: Onion peeling results in the release of alliinase enzymes that undergo exothermic reactions causing an increase in internal temperature by about 5°C when compared to a blank control. It is possible to monitor the minor changes in temperature profiles in addition to Volatile Organic Compounds (VOCs like 1-propanethiol and Volatile Alcohols).

CHALLENGES AND FUTURE SCOPE

Despite the proven effectiveness of the available technologies in well-controlled lab conditions, applying them on a larger scale is associated with numerous challenges:

Data Reliability and Peer-Review Vulnerabilities: Multi-sensor processing chains call for diligent validation of data. The presence of systematic errors in peer-reviewed papers highlights the necessity of having reproducible datasets and quality control prior to commercialization.

Sensor Selectivity and Longevity: Affordable semiconducting-type gas sensors usually exhibit a problem of cross-sensitivity to several gases at once, causing inaccuracies if the analytes of interest coincide. Moreover, their functionality may be affected by wear and chemical action over time.

FUTURE RESEARCH

Future studies must be done to develop nutrient sensors that will be capable of measuring nutrients such as protein, carbohydrate, and fat. The combination of these smart packages with mobile phone applications will aid the elderly and disabled in assessing the safety of their food at home.

CONCLUSION

IoT-enabled smart packaging is a step forward towards ensuring food safety and transparency in the supply chain. By utilizing low-cost physical sensors along with optical devices in smartphones and machine learning algorithms, today's systems can precisely determine shelf-life and decay. Even though some challenges related to sensor cross-sensitivity and data validation remain unsolved, integration of cloud analytics with elements of smart packaging enables scalability to tackle food waste reduction worldwide.

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