

# Digital Spoilage Detection Technologies for Dairy Products: A Review of Intelligent Packaging Systems for Real-Time Quality Monitoring

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## Abstract

Digital spoilage detection technologies determine the rapid microbial deterioration of dairy products caused by their high moisture content by enabling real-time freshness determination. Conventional date-based packaging fails to indicate on-time quality and safety changes, whereas digital-based intelligent packaging enables real-time monitoring of spoilage parameters by improving food safety, nutritional quality preservation, and waste reduction. Time Temperature Indicators detect thermal abuse during storage, while pH and gas-sensitive indicator films identify acidity changes and spoilage gases (CO<sub>2</sub>, H<sub>2</sub>S). RFID and QR-based tags enable real-time quality monitoring and traceability. QR codes, RFID or NFC tags, and thin-films on dairy packages serve as digital entry points where customers can scan the codes with their smartphones to access information wirelessly on product freshness, storage history, nutrition, and batch traceability. With NFC-enabled smartphones, it also helps to maintain cold chain integrity and identify whether the product is at risk of spoiling, without opening the packaging. Such technologies are used to turn physicochemical changes into visualisation or mobile-readable formats, enhancing food safety beyond the limitations of the expiration date. However, challenges like the high cost of implementation, sensor instability, limited standardisation, and user awareness prevent them from being used on a wider scale. Future research will be directed towards the development of inexpensive printable sensors, smart and biodegradable labels, and AI mobile predictive freshness systems. Digital sensing technologies help in healthy nutrition and food waste reduction while promoting smart digital dairy packaging.

**Keywords:** Digital-Based Intelligent Packaging, Real-Time Monitoring, Smart Technologies, Intelligent Packaging, Nfc-Enabled Smartphones

## Introduction

Dairy products include food items such as milk, cheese, butter, and yogurt. All these products are perishable, so the company needs to prevent spoilage and maintain proper conditions. The products mainly contain high nutrients such as proteins, fats, vitamins, and minerals, important to the health of consumers (N H Martin et al., 2021).

While the loss of these nutrients is a concern, the expiry date and spoilage of the products are major factors in food waste. Additionally, the consumption of expired products leads to serious health risks to the consumer. In the past, the expiry and spoilage of products was monitored with traditional methods. The best before dates were determined while controlling the storage of the products. Although these dates provided some guidance, spoilage can occur due to improper storage, changes in temperature, and poor storage conditions (Ellouze et al., 2021).

Milk has a freshness life of a few days or months depending on the storage condition and process used for packaging. Due to the spoilage of milk before reaching stores or after reaching stores and eventually reaching customers, there is a massive wastage of milk every year. Multilayer packaging is one technological solution for this challenge, which helps preserve milk freshness for a long time without using any preservatives and chilling at low temperatures. But sometimes milk can spoil even when packed using such packaging techniques because of heat shock and damages sustained during distribution. Consumers get to know about the freshness of milk only when they open such packs. Thus, there is a requirement to determine milk freshness quality when packed into containers (Kapse S et al., 2023).

As a result, food products were sometimes wasted due to spoilage, while also being completely safe to eat. This leads to increased food wastage and the loss of consumer loyalty and trust towards food products.

## Objectives

This review aims to comprehensively examine the mechanisms responsible for spoilage in dairy products and to critically analyse the limitations associated with conventional spoilage detection methods and expiry date labelling systems. It further seeks to evaluate recent advancements in digital-based spoilage detection technologies and assess their effectiveness in preserving nutritional quality, enhancing food safety, and reducing dairy food waste. Additionally, the review focuses on identifying current challenges, existing research gaps, and future prospects in the development and implementation of digital spoilage detection systems for dairy products.

## Microbial Spoilage of Milk and Dairy Products

The industrial quality control of milk and dairy products is particularly challenging due to their high moisture content, rich nutrient composition, and susceptibility to microbial spoilage, which can lead to off-odours, undesirable physical changes, and the formation of harmful secondary metabolites (Wouters & Geurts, 2022).

In raw and pasteurised milk, spoilage is mainly associated with psychrotrophic bacteria such as *Pseudomonas fluorescens* and *Pseudomonas fragi*, which produce heat-stable proteolytic and lipolytic enzymes that deteriorate flavour and texture even after thermal processing. Other significant spoilage organisms include *Bacillus cereus* and *Staphylococcus aureus*, which can survive processing conditions and contribute to safety concerns (N H Martin et al., 2021).

Beyond liquid milk, fermented dairy products such as yogurt, sour milk, and cheese are also prone to spoilage by yeasts and moulds, including *Debaryomyces hansenii*, *Kluyveromyces* spp., and *Candida lactis*, leading to gas formation, surface defects, bitterness, and product degradation. High-fat dairy products such as butter and cream are particularly susceptible to lipid oxidation and lipase-producing microorganisms, while cheese spoilage may involve proteolysis, late blowing defects, and surface discoloration caused by microbial growth. These spoilage processes not only reduce sensory acceptability but also shorten shelf life and result

in significant economic losses, emphasising the need for advanced monitoring and detection strategies in dairy products (Jay et al., 2025; Saha, 2024).

### Need for Digital-Based Spoilage Detection Systems

Supply chains for dairy products are difficult to manage since products are very perishable. It is important to maintain spoilage detection methods to avoid spoilage of dairy products. The industry has a feature of an uncritical evaluation of both the shelf life of the product and the storage conditions under which the product will be received and transported through the supply chain (Zhai X et al., 2022).

Conditions typical in the supply chain, including temperature abuse, delays, and unstructured transport or retail storage, lead to the rapid multiplication of spoilage microorganisms, resulting in spoilage even before the product reaches its expiration date. This results in unsafe food, disappointed customers, and economic loss for the company. Anticipating the supply chain challenges of the dairy industry, digital solutions have been proposed to track spoilage in a real-time manner, based on the actual condition and quality of dairy products (Gram & Dalgaard, 2020).

These solutions help consumers assess the quality and safety of food and track spoilage long before food goes to waste. This need for digital solutions in the dairy industry has been justified by the positive focus on the traceability, safety, and sustainability of the products (FAO, 2021).

### Conventional Methods vs. Digital Detection Techniques

**Table 1 Comparison of Conventional Methods and Digital Detection Techniques**

S. No.	Parameters	Conventional Methods	Digital Detection Techniques
1	Methods	Microbiological testing, sensory analyses, evaluation of pH and titratable acidity	QR codes, RFID or NFC tags and thin-films
2	Nature of analysis	Destructive and invasive	Non-destructive and non-invasive
3	Time requirement	Time-consuming and labour-intensive	Real-time or near real-time monitoring
4	Consumer interaction	Limited to laboratories and trained personnel	Easy interpretation by consumers and stakeholders
5	Shelf-life determination	Fixed expiry dates not reflecting actual product condition	Dynamic shelf-life assessment based on real conditions
6	Storage condition consideration	Does not account for temperature abuse or storage duration	Tracks temperature abuse and storage history

Microbiological testing, sensory analyses, and evaluation of pH and titratable acidity represent some of the traditional methods of assessing the spoilage of dairy products. While reliable, they are also destructive, time-consuming, and fail to offer real-time package assessments, monitoring, and evaluations (Deeth, 2019).

Also, expiry-date labelling is a passive approach that does not account for storage practices, temperature abuse, or duration of storage. Conversely, digital data capture technologies provide real-time, non-destructive, and uninterrupted assessments of the supply chain (Realini & Marcos, 2020; WRAP, 2020).

Smart packaging technologies have the ability to translate spoilage-enabled changes into signals that are visual or electronic and are easily interpreted by users, stakeholders, and consumers. Digital technologies like QR codes, RFID or NFC tags, and thin-films provide a more reliable means of assessing and managing the safety and shelf life of products than traditional techniques, and they are non-destructive. Digital technologies are a major improvement in methods for assessing the spoilage of food products (Tsironi & Taoukis, 2022).

## **Challenges in Conventional Microbial Detection Techniques**

Traditional cultivation and microbial quantification methods have the disadvantage of being time-consuming and incompatible with rapid quality control in the dairy industry. As a consequence of this challenge, efficient shelf-life assessment and on-time interventions may not be possible. Hence, there is an increasing demand for rapid, reliable, and cost-effective monitoring systems to assess spoilage and quality in various dairy products (Jay J M. et al., 2025).

## **Limitations of Conventional Methods for Dairy Spoilage Detection**

Sensory panels and analytical chromatographic methods associated with such detections are related to high capital costs besides the requirement of skilled personnel. These traditional methods of dairy spoilage detection are also quite time-consuming, which may not often be apt for quick industrial decisions. Early and rapid qualitative analysis of dairy food spoilage, mainly in short shelf-life dairy products, is hence of major industrial relevance. Electronic systems do not have these disadvantages and are advantageous on the grounds of lesser operational cost, lesser technical skill requirements, and automated artificial intelligence-based pattern recognition for spoilage evaluation (Jedermann et al., 2020).

## **Digital Technologies Used in Dairy Spoilage Detection**

A variety of digital technologies have been developed to sense dairy product spoilage, especially focusing on real-time measurement of microbial, biochemical, and physiological changes. Time-temperature indicators (TTIs) are widely used to measure the cumulative exposure to heat and relate it to microbial growth rate dynamics (Taoukis & Labuza, 2022).

pH and gas sensors measure changes in acidity and volatile compounds such as carbon dioxide and ammonia evolved during microbial metabolism in spoiled dairy products (Kuswandi, 2020; Huang et al., 2021).

Radio frequency identification (RFID), quick response (QR), and near-field communication (NFC) technologies provide digitally accessible platforms to measure dairy product freshness on smartphones and cloud computing services worldwide (Jedermann et al., 2020; Badia-Melis et al., 2021).

The latest developments in printable electronics and biodegradable materials have further enhanced the practicability and sustainability of digital dairy product packages (Zhai et al., 2022).

## **Sustainability and Dairy Waste Reduction**

Digital-based spoilage detection systems highly contribute to sustainability because they reduce dairy food waste while maintaining nutritional quality. Very large amounts of dairy products are thrown away due to conservative expiry labelling, not because they are spoiled. Intelligent packaging can give accurate freshness assessment so that only spoiled products are removed from circulation (FAO, 2021).

## **Limitations**

This review is based solely on existing literature and lacks experimental or real-time industrial validation, which may limit practical applicability. The focus is mainly on microbial spoilage detection, while other spoilage mechanisms and economic feasibility aspects are discussed to a limited extent. Additionally, some digital technologies reviewed are still in developmental stages, and evolving regulatory frameworks, long-term reliability, and consumer acceptance were not fully addressed (Walstra P et al., 2020).

## **Regulatory and Standardisation Aspects**

The massive growth of digital-based methods for the detection of spoilage in dairy products calls for adequate regulatory measures to ensure their credibility and reliability. Most of the intelligent systems currently in practice are legislated through general regulations for food contact materials (European Commission, 2020).

It has been stressed that there are no restrictions on the usage of sensors and indicators provided they do not migrate damaging substances to the products and do not deliver deceptive data (EFSA, 2021).

Bodies like ISO and Codex Alimentarius are increasingly realising the need to revise guidelines in order to incorporate smart and intelligent packaging systems. There will be a need to develop a framework with respect to testing and labelling policies in order to incorporate smart spoilage detection systems into existing frameworks of food safety management (EFSA, 2021).

### **Future Aspects and Research Opportunities**

Future studies indicate that the application of digital technology for spoilage detection in dairy products is tending towards the use of cost-effective, sustainable, and smart technology. AI and machine learning algorithms combined with sensors for precise prediction of shelf life and probability of spoilage, especially in dynamic environments, have become salient targets for research studies (Liu et al., 2024; Singh et al., 2023).

Biodegradable material sensors, such as those using natural dyes and cellulose, have attracted considerable interest for eliminating the hazards posed by plastic materials in food packaging technology (Zhai et al., 2022).

### **Conclusion**

Digital-based spoilage detection systems offer a practical and reliable alternative to conventional methods for assessing dairy product quality by enabling real-time monitoring of spoilage-related changes. Traditional approaches such as expiry-date labelling and laboratory testing do not consider variations in storage temperature, handling, and transport conditions, which can accelerate microbial growth and nutrient degradation. Intelligent packaging technologies, including time temperature indicators, pH- and gas-sensitive sensors, and RFID or QR-based systems, translate microbial and physicochemical changes into visual or digital signals that can be easily interpreted by manufacturers, retailers, and consumers. This condition-based evaluation improves food safety, supports better preservation of nutritional quality, and significantly reduces unnecessary dairy food waste. However, challenges such as high implementation costs, sensor stability, limited standardisation, and consumer awareness still restrict widespread adoption. Continued research into low-cost printable sensors, biodegradable materials, and AI-driven freshness prediction models is expected to enhance the feasibility, sustainability, and effectiveness of digital spoilage detection in the dairy industry.

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