

Utilization of different time temperatures indicators in packaged foods to monitor food quality and consumer impression on novel packaging technologies. – A Review

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Abstract—Active and Intelligent (A&I) packaging systems are integral to the modern food industry, serving distinct functions of protection (Active) and communication (Intelligent). Within the domain of intelligent packaging, Time-Temperature Indicators (TTIs) represent a critical technology. TTIs are designed to monitor and record the cumulative thermal history of perishable goods throughout the supply chain, distribution, and storage. Their primary function is to provide a direct, visual indication of temperature deviations or excursions, allowing stakeholders and consumers to assess potential product degradation. This capability is essential for ensuring food quality and safety. However, despite their theoretical benefits, the widespread commercial application of TTIs is hindered by significant limitations. Key challenges include the potential for toxic substance migration from the indicator to the foodstuff, inaccuracies in thermal monitoring, and prohibitive costs that impede large-scale adoption. This review provides a comprehensive overview of the operating principles governing various TTI types. It further examines commercially viable designs and indicators currently utilized in the market. Finally, the paper synthesizes existing market research and consumer surveys to analyze the present state, future prospects, and barriers to consumer adaptation of TTI technology.

I. INTRODUCTION

Traditionally, packaging has served four fundamental functions: containment, protection, convenience, and communication. Beyond simply holding a product, packaging is a primary marketing vehicle, conveys essential consumer information, and enhances usability. However, contemporary market dynamics and shifting consumer preferences have created a pressing need for packaging solutions that transcend these traditional roles. Key drivers include a consumer

demand for minimally processed foods with fewer preservatives, increasingly stringent regulatory requirements, the globalization of the food supply chain, heightened concerns over food safety, and the emerging threat of food bioterrorism. These factors necessitate the continuous development of innovative packaging with enhanced functionalities.

Traditional packaging systems are characterized by their passive and inert nature. Their primary role is to provide mechanical support and to shield the food product from detrimental external influences, such as microbiological and chemical contamination, light, oxygen, and pests (Robertson, 2006). In this conventional model, interaction between the food and the packaging material is ideally minimized. While historical methods for extending shelf life relied on interventions like the addition of preservatives or the modification of packaging layers, a new paradigm has emerged (Robertson, 2006). The evolution from this passive protective role to one that actively modifies the product's internal environment defines "active packaging." Concurrently, the enhancement of packaging's communicative function to report on the product's condition defines "intelligent packaging." While the concepts of "active packaging" and "intelligent packaging" are closely related and often discussed in tandem, a critical distinction exists between them. It is noteworthy that the definitions of these terms can vary among authors in the field.

II. CLASSIFICATION OF FOOD CONTACT MATERIALS

The Framework Regulation on Food Contact Materials (1935/2004) offered the following definition:

2.1 Active Packaging

“Active materials and articles” are defined as materials and articles that are intended to extend the shelf-life or to maintain or improve the condition of packaged food. They are designed to deliberately incorporate components that release substances into, or absorb substances from, the packaged food or the environment surrounding the food.

2.2 Smart Packaging

Intelligent materials and articles are defined as substances and objects designed to monitor the state of packaged food or the environmental conditions surrounding the food product. An alternative technology, "smart packaging," offers solutions to many challenges associated with the deterioration of packaged food. Smart packaging is often described as a combination of both active and intelligent systems, which can collectively increase shelf-life and communicate food quality status throughout the supply chain. However, many authors use "intelligent packaging" and "smart packaging" synonymously (Biji et al., 2015; Kuswandi et al., 2011; Pacquit et al., 2006; Park, Kim, Lee, & Jang, 2015), as both can feature "smart" functions like sensors (biosensors, chemical, gas), indicators (TTIs, freshness, integrity), RFID tags, or barcodes (Kerry, Grady, & Hogan, 2006). In commercial practice, the technologies are often applied specifically as either active or intelligent packaging. Intelligent systems, for instance, typically employ sensors or indicators to detect unfavorable conditions during distribution and storage.

2.3 Intelligent Packaging

Intelligent packaging utilizes the communication functions of packaging materials to record changes in the internal and external environments, thereby informing users about the status of the packaged food. Food quality must be continuously monitored during distribution, storage, and sale and potentially by the final consumer as the microenvironment within the package can alter product quality (Kuswandi, 2018). Traditional evaluation methods, such as biological, physicochemical, and serological techniques, are often time-consuming, labor-intensive, and require specialized personnel. Consequently, there is a distinct need for simple, rapid, reliable, and sensitive methods to monitor food quality and safety (Kuswandi, 2018; Kuswandi et al., 2011; Thakur & Ragavan, 2013). This highlights the fundamental difference between the

systems: intelligent packaging is responsible for observing the environment and processing data, whereas active packaging is responsible for taking action (e.g., releasing an antimicrobial) to protect the food product.

According to major reviews (Kerry et al., 2006; Stauffer, 2005; Yam et al., 2005), intelligent packaging systems primarily include the following components:

- Indicators:
 - Time-temperature indicators (TTIs)
 - Integrity or gas indicators
 - Freshness indicators (monitoring microbial or pathogen spoilage)
- Barcodes and radiofrequency identification (RFID) tags
- Sensors:
 - Biosensors
 - Gas sensors
 - Fluorescence-based oxygen sensors

A "sensor" is defined as a device used to quantify a chemical or physical property, responding to energy or matter with a signal (Kerry et al., 2006; Kress-Rogers, 1998).

"Indicators," conversely, are devices that signify the presence, absence, or concentration of an analyte, or the degree of reaction between analytes, typically via a color change (Hogan & Kerry, 2008; Kuswandi, 2018). A key distinction is that indicators lack the specific receptor or transducer of a sensor; they provide information solely through visual changes related to food conditions (e.g., time, temperature, or pH) (Kuswandi, 2018; Mills, 2005).

III. TIME-TEMPERATURE INDICATOR

Temperature is a critical factor determining the storage stability of perishable food products. Abrupt fluctuations in temperature introduce significant concerns regarding the quality integrity of processed food materials. As a result, contemporary food processors and suppliers have instituted rigorous protocols for monitoring the temperature of food materials at every stage of the supply chain, extending from harvest through to final consumption (Giannakourou et al., 2005). Time-Temperature Indicators (TTIs) provide essential data concerning the

duration and extent to which food products have been exposed to temperatures exceeding stipulated thresholds during transportation and storage. This capability is particularly vital for generating temperature abuse alerts for chilled or frozen commodities (Pavelkova, 2013). Currently, the convention of printing an expiration date on product packaging represents the primary means of communicating information regarding product durability. Nevertheless, this static practice is inherently limited, as it neither guarantees product safety nor offers real-time insight into the product's life cycle post-printing. Consequently, numerous entities within the food processing industry are actively pursuing the development of comprehensive traceability technologies. These technologies aim to facilitate continuous monitoring of food temperature across the entire supply chain, from "farm to fork," thereby strengthening the safety and security of the supply path from the producer to the end consumer.

An ideal Time-Temperature Indicator (TTI), or integrator, is conceptualized as a simple, economical device engineered to exhibit an easily quantifiable, time-temperature-dependent change that accurately reflects the complete or partial thermal history of the food product to which it is affixed (Taoukis and Labuza, 1989).

Time-Temperature Indicators (TTIs) must meet essential performance and safety criteria to ensure their effective adoption and reliability. These devices must be compact, affordable, dependable, and easily integrated into existing packaging systems. Crucially, they must be non-interfering, meaning they shouldn't compromise the food product's shelf life through susceptibility to environmental factors (such as light, humidity, or air pollutants) or mechanical stresses (like pressure or friction). An ideal TTI provides a simple, continuous, and universally comprehensible indication that is accessible to all stakeholders (producers, retailers, consumers) and is quantifiable through both visual inspection and electronic means. Furthermore, TTIs must demonstrate no deleterious effects on human health or the environment (Taoukis, 2010; Taoukis and Labuza, 2003). The core functionality relies on the temperature-dependent rate of change within the TTI system, which is engineered to mirror the kinetics of food spoilage; as temperature increases, the reaction rate accelerates. The resulting visible change thus offers a cumulative indication of the

integrated time and temperature exposure history. TTIs are fundamentally categorized based on their operating principles into chemical, physical, enzymatic, and biological systems. Continuous academic and industrial research is focused on developing novel TTI systems, particularly those that utilize various color change mechanisms.

3.1 Time-Temperature Indicator (TTI) Classification

3.1.1 Classification Based on function

Time-Temperature Indicators (TTIs) are classified into three types: Critical Temperature Indicators (CTI), Critical Temperature/Time Integrators (CTTI), and general TTIs. CTIs act as simple go/no-go gauges, signaling exposure to an anomalous temperature for a duration sufficient to damage quality or safety, making them ideal for highly sensitive products like frozen goods where even brief temperature excursions are detrimental. CTTIs are more sophisticated, recording the history of accumulated thermal exposure *above* a critical threshold temperature, thus reflecting the cumulative energy input that accelerates quality- or safety-critical reactions (like microbial growth or enzyme activity) that begin to manifest at measurable rates above that temperature. The third category, simply called TTIs (the most widely used type), is often subdivided into Temperature Indicators, which continuously monitor instantaneous temperature and show a rapid, often permanent, color change upon exceeding the safe limit (critical for chilled foods), and Time-Temperature Integrators, which reflect the combined effect of time and temperature over the entire storage period.

3.1.2 Classification Based on Temperature History

TTIs are categorized into partial history indicators and full history indicators. The former only signals whether a product has been exposed to a critical maximum temperature threshold, providing a simple pass/fail indication. Conversely, full history indicators (Kerry et al., 2006; Taoukis, 2001) provide a continuous, cumulative record of the product's time-temperature history throughout the entire distribution chain. This enables a continuously developing response, offering greater sensitivity to thermal abuse and better correlation with product quality loss over time.

3.1.3 Classification Based on Operation Principle

TTIs function by undergoing an irreversible change a visible color shift driven by a process whose rate is directly dependent on time and temperature. These processes can be physical (mechanical), chemical, electrochemical, enzymatic, or microbiological.

3.1.3.1 Physical TTIs

Diffusion-Based TTIs: These indicators rely on a colored substance (e.g., a fatty acid ester) diffusing through a porous matrix at a rate proportional to the ambient temperature. When the temperature exceeds a critical response point, the substance melts and migrates, producing a visible, cumulative response.

3M-Monitor Mark: A commercial example where a colored fatty acid ester diffuses through a porous wick when temperatures rise above its melting point.

Tempix FreshCode: This system uses a material that turns liquid above a specific temperature, irreversibly destroying the readability of an associated barcode. Diffusion-based TTIs are commercially successful due to their wide working temperature range and simple manufacturing but face challenges regarding the safety and accuracy due to the potential exudation of colored material.

3.1.3.2 Nanoparticles-Based TTIs

These utilize the thermochromic properties of noble metal nanoparticles (Ag, Au), where changes in heat absorption alter the surface morphology, size, or shape, causing a shift in their optical properties and, thus, their color. Although promising, their high cost and the potential for particle migration pose safety and commercial hurdles.

Electronic Time-Temperature Indicators (TTIs): These are sophisticated thermal sensors that convert temperature into electrical signals, processed by a logger/microprocessor to record the thermal history (Zweig et al.) or alter the properties of an electronic component (Haarer et al.). While offering high precision, their bulkiness and high cost have limited their widespread commercialization as disposable labels.

3.1.3.3 Chemical TTIs

Polymerization-Based TTIs: The earliest type, these are based on the solid-state polymerization of a monomer (typically diacetylene) when exposed to high temperatures. The irreversible 1,4-addition

polymerization forms a polymer, polydiacetylene (PDA), causing a color change (e.g., from colorless to blue/dark) that increases with accumulated thermal exposure. **Fresh-Check®/Freshness Monitor** and **HEATmarker®:** Commercial examples based on diacetylene polymerization, where the product is deemed expired when the inner color matches or is darker than a reference color. A major limitation is the need for very low-temperature storage for activation and potential safety concerns regarding polydiacetylene compounds.

Photochromic-Based TTIs: These are built on a photochromic substance (e.g., spiropyran or spirooxazine) which is initially activated by UV light (charged), causing a color change. The color then fades over time at a rate proportional to the ambient temperature (thermally induced fading). **OnVu™:** A printable system based on the spiropyran solid-state reaction, where the blue 'core' color fades back to colorless as the product's shelf life diminishes. The main challenge is preventing unwanted photo recharging or photobleaching from ambient light, which would compromise accuracy.

Redox Reaction-Based TTIs: These indicators exhibit a color change resulting from a time- and temperature-dependent redox reaction or light-induced redox reaction (e.g., the Keep-it system, or those using anthraquinone derivatives). While conceptually simple, their accuracy can be compromised by the impact of atmospheric oxygen, and the use of certain chemicals (like anthraquinones) raises safety concerns.

3.1.3.4 Enzymatic Time-Temperature Indicators

Enzymatic TTIs (e.g., CheckPoint™) are based on the hydrolysis reaction of an enzyme (like lipase) with a substrate, which alters the pH of the system and subsequently changes the color of a pH indicator. The reaction rate, and thus the rate of color change, is directly proportional to temperature. These TTIs are advantageous for their low cost, stable performance, and ease of control (by adjusting factors like enzyme/substrate concentration and pH) to match the degradation kinetics of a specific product. They are activated by mechanically mixing the enzyme and substrate, which are stored separately.

3.1.3.4.1 Recent Advancements in Enzymatic Time-Temperature Indicators (TTIs)

Building upon the established principle of utilizing enzyme hydrolysis to correlate reaction rates with cumulative time and temperature exposure, recent academic research has explored diverse enzymatic TTI systems beyond the conventional lipase-based indicators.

Wu investigated a system where urease catalyzes the breakdown of a urea substrate to produce ammonia. This reaction increases the system's pH, which is visually registered by a phenol red indicator changing color. The formulation included a disodium hydrogen phosphate/potassium dihydrogen phosphate buffer to ensure the catalytic reaction operates within a specific pH range, allowing for accurate kinetic parameter discussion.

Kim et al. developed a TTI based on the enzyme laccase. The system components include laccase solution, guaiacol (the substrate for laccase), a stabilizer like bovine serum albumin (BSA), and a sodium acetate buffer. Laccase catalyzes the oxidation of guaiacol, resulting in a discoloration that indicates the cumulative time-temperature exposure.

Qian et al. created a TTI utilizing glucoamylase, which catalyzes the hydrolysis of dextrin. An iodine solution is used as the indicator, with the extent of the color change reflecting the cumulative time-temperature effect.

Wu also detailed a system using alkaline lipase to hydrolyze glyceryl tributyrates (substrate). This reaction causes the TTI's pH to decrease, leading to a progressive color shift from dark blue to bright yellow in the presence of a thymol blue indicator and a Gly-NaOH buffer.

Despite extensive academic research and numerous global patents for these diverse enzymatic TTI systems, very few have successfully transitioned into commercially accessible products. The objective of future research is to enable commercial application by developing simple-to-read enzymatic TTIs with consistent performance.

Enzyme Diversification: Creating a wider variety of stable and safe enzyme types suitable for TTI formulations. **Expanded Application Range:** Utilizing the simple control properties of enzymatic TTIs to broaden their use. This involves adjusting the concentrations of the substrate or enzyme solution to fine-tune the reaction rate and the apparent activation energy (E_a), thereby matching the TTI kinetics to specific food products. **Formulation Optimization:**

Modifying the formulations of coenzymes, inhibitors, and buffers to tailor the TTI system's performance, allowing for the creation of numerous systems calibrated for food items. **Applied Research Focus:** Conducting more research to widen the calibration range, sharpen the chromatic (color) change for easier reading, and minimize the influence of external factors other than time and temperature on the indicator's performance.

3.1.3.5 Biological Time-Temperature Indicators (TTIs)

Biological TTIs, specifically Microbial TTIs, are considered an advanced class of indicators because their response directly correlates with microbial food spoilage, the primary cause of fresh food decomposition. These systems leverage the growth and metabolism of microorganisms to provide an indication of cumulative time-temperature abuse.

The underlying principle of microbial TTIs is that microbial growth and metabolic activity are accelerated by higher temperatures. The indicator system incorporates carefully selected microorganisms (commonly yeasts and lactic acid bacteria, such as *Lactobacillus* and *Streptococcus*) along with a nutritive medium and a pH-sensitive color indicator. As the microorganisms grow and utilize the carbon source in the medium, they generate lactic acid or other metabolites. This acid production lowers the pH of the medium at a rate proportional to the time-temperature profile experienced by the product. The resulting pH reduction causes an irreversible color change in the indicator dye, visually displaying the accumulated thermal effect and, theoretically, the product's remaining shelf life.

Topcryo (TRACEO): This commercial TTI is a microbiological reaction-based system composed of three layers. The layers contain lactic acid bacteria (e.g., *C. maltaromatics*), a nutritive medium to support bacterial growth, and a color indicator (e.g., acid fuchsin). The TTI is activated when the layers are mixed (broken) upon exposure to a temperature higher than a critical threshold. The ensuing enzymatic reaction causes a visible color change, typically from green to red, as reported by EFSA (2013).

eO Indicators: These are simple, cost-effective adhesive colorimetric labels consisting of a dyed indicator and a flower-petal-shaped nutritive medium. Lactic acid bacteria are inoculated into the label to

match the requirements of the food product. The indicator is activated upon thawing after being applied and frozen. As the product is exposed to varying time and temperature conditions, the bacteria grow at a proportional rate, releasing lactic acid and causing the indicator dye to change color as the medium's pH decreases.

Microbial TTIs have a wide array of applications in various sectors like Food Monitoring: Tracing the quality of food in grocery stores and monitoring the safety of prepared foods, such as cooked meals and sandwiches, in the catering industry and Healthcare: Tracking the cold chain integrity of temperature-sensitive biological products, including vaccines and blood collection bags.

3.2 Novel Time-Temperature Indicator (TTI) Systems
Recent research has introduced innovative TTI systems that utilize advanced materials and physical principles to monitor the cold chain, offering advantages in cost, durability, and integration.

3.2.1 TTI Based on Photonic Lattice Change

An irreversible TTI has been developed utilizing a photonic crystal (PC-TTI). The core mechanism relies on the relationship between the photonic crystal's band-gap change and temperature, which results in a distinct, often dramatic, visible color shift.

Activation: The TTI is activated by external heat, which forces the hardener out of its pouch to react with the photonic crystal material. This reaction causes the crystal structure to enter a fixed state.

Response: Once fixed, the PC-TTI can record the continuous change in temperature over a preset period or signal if the temperature exceeds a specified threshold.

Advantages: The system is irreversible, does not require an external electrical source, and is cost-effective and lighter than electronic recorders. Crucially, the photonic crystal is separated from the hardener prior to use, allowing for long storage stability. Its design also allows for easy integration with printed barcodes for use as smart labels.

3.2.2 TTI Based on Thermochromic Polymer/Dye Blends

Another emerging system utilizes the phase separation between dye molecules and a polymer host. This TTI incorporates polymers that act as built-in threshold

temperature sensors. The operational principle is tied to the polymer's glass transition temperature (T_g) and the translation mobility of the embedded dye molecules:

Mechanism: When the polymer matrix is heated to its T_g or above, the dye molecules' state changes from isolated forms to aggregated forms. This change is irreversible for the polymer matrix.

Detection: The aggregation process alters the dye molecules' characteristics, specifically their UV absorption and/or fluorescence emission spectra, due to phenomena like charge transfer, excimer formation, or conformational changes (78, 79).

Significance: When the external temperature surpasses the T_g , the resulting change in the absorption or emission spectra visually indicates that the food's shelf life has been reached, providing a clear warning of potential deterioration (80).

IV. RESULTS & DISCUSSION

The active packaging market is poised for substantial growth, projected to reach US\$31.924 billion by 2026 with a Compound Annual Growth Rate (CAGR) of 6.62% (Research and Markets, 2021). This expansion is largely driven by the urgent global need to address massive food loss and waste, estimated at over 1.3 billion metric tons annually by the Food and Agriculture Organization (FAO), which incurs significant financial burdens on the food industry. Consequently, designing adequate packaging to extend the shelf-life of perishable goods, such as India's fresh produce, dairy products (global milk production reached 906 million tons in 2020), and baked goods, has become paramount. The global market for Active, Intelligent, and Smart (AI&S) food and drink packaging is continuously expanding due to heightened food and safety concerns, increasing consumer purchasing power, and a willingness to pay more for health assurance. Other influential factors include the growing demand for prepared and convenience foods, retailer demands for longer product shelf lives, and environmental considerations regarding recycling and biodegradable packaging. The fastest growth within the AI&S segment is expected to be propelled by the use of Time-Temperature Indicators (TTIs), which help verify freshness, and the development of smart packaging systems offering product differentiation and traceability at competitive

prices. This trend is observed globally, particularly in major economies like the United States (projected to be the largest market), Japan, Australia, Germany, China, Thailand, India, and France.

Despite the robust market outlook, consumer acceptance of smart packaging remains a critical challenge. Studies indicate that a majority of consumers are either dissatisfied or neutral with existing conventional packaging, signaling a demand for alternatives, especially as consumers increasingly seek natural, minimally processed, and additive-free foods (Li et al., 2020). However, consumer awareness is initially low, with only 17% of the population popular with the term 'smart packaging' (Daoud and Trigui, 2019). When acceptance was surveyed, the results were positive: 56% found both Active Packaging (AP) and Intelligent Packaging (IP) acceptable, with acceptance rising significantly when presented with product-specific applications. For instance, AP acceptance reached 68% for fruits and vegetables, while IP acceptance peaked at 75% for dairy products and 73% for meat. Although consumers showed an interest in novel packaging and were willing to adopt the technology, studies initially found opposition to paying more, though this resistance decreased after consumers were educated on the benefits (O'Callaghan and Kerry, 2016).

The primary barriers against the purchase of smart packaging are predominantly psychological and functional. Psychological barriers include a perceived risk barrier (subdivided into physical, environmental, functional, and social risks), a tradition barrier, and an image barrier (Young et al., 2020). Consumers are often concerned about potential risks, such as harmful components in the packaging materials, and worry that innovative packages might be misleading, preferring to trust sales under established brands (Aday et al., 2015). Functional barriers, like the presence of active packaging sachets, can also lead to rejection if their purpose is not clearly explained to consumers (Wilson et al., 2018). Furthermore, cost remains a factor, as manufacturers in the narrow-margin food sector require lower prices for widespread adoption. To maximize acceptance, the key strategy is education and transparency: efforts must be made to spread awareness through effective media advertising (preferred by 40.55% of consumers) and thorough information campaigns on labels. Utilizing the emotional value of well-known brands can reduce risk

perception, and focusing on the benefits while retaining transparency on potential downsides is the proposed solution to increase trust and bridge the gap between perceived risks and benefits (Greehy et al., 2011). Ultimately, more applied research is needed to deepen the understanding of consumer acceptance in this evolving area.

V. CONCLUSION

The development of Time-Temperature Indicators (TTIs) has produced a wide array of designs based on diverse physicochemical properties including diffusion, polymerization, and enzymatic reactions all strategically aligned to match their response kinetics with the critical temperature profiles of specific food products. While numerous commercially viable TTI designs exist for effective cold chain monitoring and supply chain management, their widespread adoption and full market penetration are currently hampered by three critical implementation barriers: cost-effectiveness, safety, and environmental concerns. High manufacturing costs, particularly for sophisticated electronic and nanoparticles-based TTIs, limit profitability in the narrow-margin food sector. Furthermore, safety issues, such as the potential migration of nanomaterials or the toxicity of compounds in some chemical TTIs, alongside growing demands for environmental sustainability, must be comprehensively addressed. Concurrently, while market research confirms the Active, Intelligent, and Smart (AI&S) packaging market is expanding and consumer interest in health and traceability is high, this consumer acceptance is obstructed by the high cost and a pervasive lack of knowledge about the technology. To maximize acceptance and propel the future success of TTIs, a dual strategy is essential: advancing research to yield cost-effective and environmentally safe indicators, and concurrently implementing effective and transparent educational and communication campaigns to inform consumers, dismantle psychological barriers, and establish trust in smart packaging solutions.

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