www.sasinsights.com ISSN: 3107-135X

SCIENCE AND SOCIETY INSIGHTS

Sci Soc Insights (2026), 5: 1-18 Review Article

Shelf life Extension Strategies for Bakery Products: Formulation, Processing, and Packaging Approaches

Sawera Hayat, Wali Ullah, Saleha Tariq, Izza Razzaq and Alisha

Department of Food science and technology, Government College University Faisalabad
**Corresponding author*: sawerahayat22@gmail.com

Article History: 25-290 Received: 24 Nov 2025 Revised: 29 Dec 2025 Accepted: 10 Jan 2026 Published Online: 2026

Citation: Hayat S, Ullah W, Tariq S, Razzaq I and Alisha, 2026. Shelf life Extension Strategies for Bakery Products: Formulation, Processing, and Packaging Approaches. Sci Soc Insights, 5: 1-18. https://doi.org/10.65822/j.sasi/2026.001

ABSTRACT

Bakery products spoil quickly due to staling, microbial deterioration, moisture migration, and oxidative changes, leading to massive global food waste and quality losses. Although many preservation methods can be found, the comparative efficacy and industrial scale for these methods are fragmented in the literature. This review critically examines biochemical and physicochemical explaining mechanisms that contribute to the deterioration of bakery products and synthesizes current deterioration mechanism of bakery products with a focus on recent progress in exploring formulation, processing, and packaging-based improvements for increased shelf life. Particular attention is paid to natural antimicrobials, antioxidant systems, anti-staling enzymes, hydrocolloids and sourdough fermentation, as well as new non-thermal technologies of high-pressure processing, UV-C, cold plasma and irradiation. Advances in modified atmosphere packaging, active and smart packaging, and biodegradable edible coatings are also analyzed in various terms of performance and clean label compatibility. By compiling the existing evidence from current knowledge within the sub-disciplines of formulation, processing and packaging, this review provides a focus for the current preservation frameworks and highlights some of the key research gaps relevant for commercial bakery applications. The results give credence to the development of technologically feasible, clean-label, and sustainable strategies for extending the shelf life of modern bakery products.

Keywords: bakery product; shelf life; biodegradable; anti-staling enzymes; non-thermal technologies; smart packaging

INTRODUCTION

The global bakery industry is one of the most dynamic and diverse segments of the food market, as bakery products are referred to as staple foods in many regions of the world and convenient snacks in others. Their popularity is increasing further, thanks to urbanization, evolving work routines and consumers increasing preference for ready to eat food options that are inexpensive and versatile (Kostyuchenko et al., 2025). From traditional bread and flatbread to cakes, pastries and cookies, bakery is wide ranging in terms of texture and flavor offering to meet varied cultural and nutritional demands (Kothari et al., 2024). In recent years, product development innovation, like high-fiber breads, gluten-free product development, whole grain product development, and functional bakery products enriched with bioactive compounds have further expanded the growth of the market. Despite this diversity and technological advancement, however, maintaining consistent quality and ensuring prolonged consumer acceptability during storage are major challenges of the bakery industry (Kostyuchenko et al., 2025).

Shelf life is one of the most important attributes, which has a major impact not only on the marketability of bakery products but also on the economic feasibility of production. Short shelf life causes enormous financial losses from the return of the products, spoilage and wastage in the supply chain (Noshirvani & Abolghasemi Fakhri, 2025). For consumers the perception of freshness, softness, aroma, and general sensory appeal have a big influence on purchase decision and the minute decrease of these attributes may cause the rejection of the product. In addition to preferences for quality, safety issues are important. Bakery products, particularly those containing high moisture content or enriched filling are vulnerable to microbial spoilage by molds, yeasts and bacteria that may lead to potential health risks and compliance issues to bakery producers (Sowmya & Ramalingappa, 2025).

The deterioration of bakery products is determined by a set of multiple and frequently interrelated biochemical and physicochemical processes that combined effect on product stability (Taglieri et al., 2021). Microbial spoilage, especially mold growth, is one of the most common food quality deterioration factors affected by water activity, storage temperature, handling and post-baking contamination. Staling, a phenomenon which is mostly caused by starch retrogradation, results in crumb firming, a loss of moisture from the crumb to the crust and results in a change in structural arrangement, eventually reducing perceived freshness (Vermelho et al., 2024). Lipid oxidation is also a major source of quality deterioration particularly in products containing high levels of fat and unsaturated oils. Additionally, the movement of moisture within the matrix of a product or between the product and its packaging environment will result the accelerated rates of microbial growth and textural deterioration (Awulachew, 2024; Machado et al., 2023).

In response to these challenges, interest is booming from scientific and industrial sectors to find modern, safe and sustainable strategies for extending shelf life that can meet the changing expectations of consumers. Clean-label demands have shifted the focus on natural antimicrobials, antioxidants, enzymes and fermentation-based solutions to increase the stability of the product without the heavy use of chemical preservatives (Kostyuchenko et al., 2025; Wang et al., 2025). Parallel developments in processing technologies such as vacuum cooling, hurdle technology, high pressure processing, UV-C treatments, cold plasma and other non-thermal processing methods provide innovative means for reduction of microbial load and retarding deterioration (Chacha et al., 2021). Packaging innovations such as modified atmosphere packaging, active packaging films and biodegradable edible coatings also further contribute to freshness maintenance during distribution and storage (Qu et al., 2022).

Factors Affecting Shelf life of Bakery Products

The shelf life of bakery products is influenced by a combination of biological, physicochemical, and environmental factors. Knowing these factors will be vital in developing an effective preservation means that do not compromise product quality, safety and acceptability by consumers. The key factors influencing the evolution of shelf life in bakery products are microbial spoilage, physicochemical deterioration and storage or environmental conditions, which can act independently or synergistically to increase quality deterioration (Mollakhalili-meybodi et al., 2023; Noshirvani & Abolghasemi Fakhri, 2025).

Table 1: Major deterioration pathways in bakery products and control strategies

Deterioration pathway	Primary drivers	Quality indicators	Key mitigation approaches
Microbial spoilage	High water activity, oxygen, post-bake contamination	Visible mold, off-odors	MAP, antimicrobials, hygienic handling
Staling	Starch retrogradation, moisture redistribution	Crumb firming, dryness	Anti-staling enzymes, emulsifiers, hydrocolloids
Moisture migration	Packaging permeability, RH gradients	Soggy crust, dry crumb	Barrier films, humectants
Lipid oxidation	Oxygen, light, unsaturated fats	Rancid flavor, aroma loss	Antioxidants, oxygen scavengers

Microbial Spoilage

Microbial contamination is one of the most important factors that limit the shelf life of bakery products, especially in products that have a high moisture content such as breads, cakes, and cream-filled pastries (Sowmya & Ramalingappa, 2025). Of the spoilage organisms, the most common is mold of which species of *Aspergillus* and *Penicillium* are commonly reported within different bakery products. These molds can grow under various environmental conditions with a tolerance for moderate water activity and are resistant to processing stresses and are therefore quite difficult to control (Pitt & Hocking, 2022). Yeasts are also important as spoilage agents, particularly of bakery products in which the sugars are often sweet and enriched and hence a favorable setting for fermentation related growth (Vermelho et al., 2024). Certain bacteria, while less frequently, may be involved in spoilage due to the formation of off-flavours, acidification or changed texture of the product, which leads to low consumer acceptability (Esmi et al., 2025; Noshirvani & Abolghasemi Fakhri, 2025).

The growth and activity of these microorganisms is greatly affected by water activity and moisture content of the bakery product. High water activity promotes microbial growth while reduction by drying, the use of humectants or certain ingredient formulations will slow the rate of microbial growth considerably (Esmi et al., 2025). Further, product pH, sugar content and surface application of preservatives or natural antimicrobials play a key role in modulating stability of microbials. Environmental factors such as temperature of storage, its relative humidity, and after-baking handling affect more the rate of spoilage (Morassi et al., 2022; Vermelho et al., 2024). Therefore, effective microbial management, i.e., combination of formulation, processing and storage intervention is essential to ensure safety as well as prolonged shelf life of bakery products.

Physicochemical Deterioration

In addition to microbial spoilages, bakery products are subject to significant physicochemical changes during storage that have an adverse effect on their quality and shelf life (Taglieri et al., 2021). One of the most common deterioration is staling, which is caused mainly by the retrogradation of the starch molecules in the crumb (Scott &

Awika, 2023). During retrogradation, there is a re-association and crystallization of the amylopectin and amylose chains which eventually results in firming of the crumb and loss of the softness and freshness overall. Moisture migration between the crumb, crust and packaging environment further promotes the degradation causing either dryness or sogginess depending on the storage conditions (Nugrahedi et al., 2025). These textural changes are especially important in the bread and cakes industry, where bread and cake freshness is closely related to consumer acceptance.

Lipid oxidation is another important physicochemical contributor to bakery product quality, particularly those with fats such as pastries, cookies and enriched breads. Oxidative reactions cause rancid flavors, off-odors and in unsaturated fats can cause unhealthy reduction of nutritional value (Kasaai, 2025). The rate of oxidation of lipids depends on factors like temperature, oxygen availability, nature of fats and presence of pro-oxidants or antioxidants. Additionally, other physicochemical changes such as maillard reactions, proteins getting denaturated as well as changes in the colour qualities can degrade the sense of quality in the most subtly over the time (Khalid et al., 2023; Machado et al., 2023). Collectively, these mechanisms illustrate the importance of accurately controlling formulation, ingredient choice and storage conditions in an effort to utilize all available adaptations and strategies for the preservation of the freshness, flavor and overall acceptability of bakery products throughout the shelf life.

Environmental and Storage Conditions

Environmental and storage conditions have a very significant influence on the shelf life and overall quality of bakery products. Temperature is one of the most influential factors affecting the growth of the microorganisms and the physicochemical deterioration (Cappelli et al., 2022). Elevated storage temperatures may advance the process of staling and lipid oxidation as well as microbial growth, whereas temperatures which are lower may slow these processes but may contribute to condensation and localized moisture build-up, especially in packaged products. Relative humidity also has a direct effect on water activity of water inside the product, with various implications on moisture migration, microbial stability and textural integrity (Xing et al., 2021). Humidity environments that are high will favor increased mold growth, and very low humidity can cause product drying and hardening leading to loss of product freshness and consumer acceptability (Alp & Bulantekin, 2021).

Packaging permeability and design are equally important in the control of the environmental effects. Moisture permeable and oxidizable packaging can allow oxidative reactions and moisture exchange with the environment leading to rapid staling and spoilage (Habiba et al., 2025). On the other hand, barrier packaging materials have the capability to create an optimum environment to minimize moisture losses, oxygen contamination, and slow down microbial growth (Awulachew, 2024). Moreover, handling during the post baking stage such as, transportation, storage or exposure to contamination may enter microorganisms or physical stress which may hamper quality. Therefore, it is important to optimize the storage conditions, packaging material, and handling practice to preserve the sensory quality, nutritional quality and microbial value of bakery products and to prolong its marketable shelf life (Chou et al., 2023; Sowmya & Ramalingappa, 2025).

Critical evaluation deterioration mechanisms

Although microbial spoilage, staling, moisture migration, and lipid oxidation have been discussed independently, they strongly depend on the type and formulation of the product. High moisture products breads and cakes are restricted mainly by the growth of mold whereas low moisture, fat-rich products such as cookies are susceptible to oxidative change. Importantly, these mechanisms often interact, such as moisture migration that may cause the gas and the retrogradation of starch to closely promote one another, increasing quality loss. For this reason, preservation methods addressing only one type of deterioration pathway are usually unsuccessful in providing strong shelf life extension. This points to the need to use integrated, multi-mechanisms approaches for the control of bakery products for effective preservation.

Ingredient Based Strategies for Shelf life Enhancement

Ingredient based intervention are among the most widely implemented interventions to raise the shelf life of bakery products. The selection and combinations of ingredients can have a large impact on the stability of the microbe, physicochemical properties, and sensory quality (Igual & Martínez-Monzó, 2022; Kim et al., 2025). These tactics are favored by manufacturers looking to keep food even more available in preservation, clean label, and move away from relying on synthetic preservatives. Key ingredient-based approaches such as natural antimicrobial, antioxidants, enzymes, emulsifier, hydrocolloid and the fermentation-based solutions.

Table 2: Formulation-based approaches for shelf life extension in bakery systems (Kim et al., 2025)

Strategy	Primary function	Clean-label suitability	Typical applications
Natural antimicrobials	Mold inhibition	High	High-moisture breads, cakes
Antioxidants	Oxidation control	Medium–High	Fat-rich bakery products
Anti-staling enzymes	Softness retention	High	Bread, soft rolls
Emulsifiers	Structure stabilization	Medium	High-volume breads
Hydrocolloids	Moisture retention	High	Cakes, gluten-free products
Sourdough fermentation	Microbial and textural stability	Very high	Artisan and premium breads

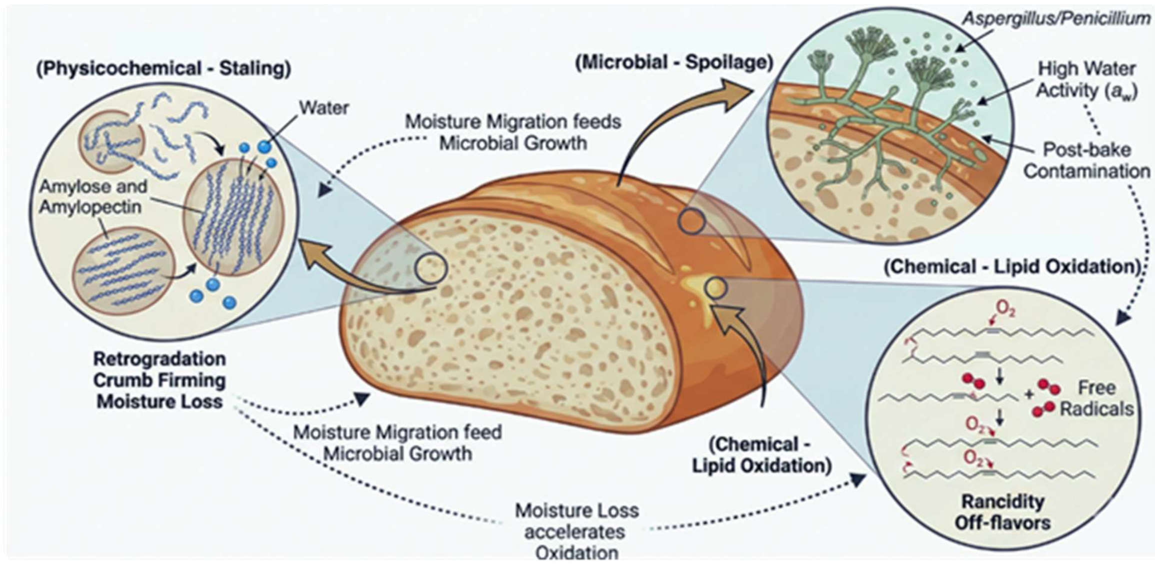

Fig.1: Mechanisms of Bakery Product Deterioration (Awulachew, 2024; Kasaai, 2025)

Natural Antimicrobials

Natural antimicrobials from plants, essential oils, spices, and phenolic compounds have developed a lot of interest in the last years in connection with the growing consumer demand for minimally processed and clean-label bakery products (Noshirvani & Abolghasemi Fakhri, 2025). These bioactive compounds could be used as an alternative to synthetic compounds with preservative functions since they provide microbial inhibition without the effect of synthetic preservatives, such as removing naturalness or safety perception (Teshome et al., 2022). Essential oils from cinnamon, clove, oregano, thyme and rosemary, phenolics-rich extracts from herbs and spices have shown great antifungal and antibacterial properties which are effective against some of the most common types of bakery spoilage organisms such as molds (Aspergillus, Penicillium), yeasts, and certain types of bacteria (Mateo et al., 2025). The increasing preference for use of natural preservatives is in line with the regulatory trends shifts in many countries towards restricted or limited use of synthetic additives and this has further boosted the use of plant-derived antimicrobials in the bakery industry (Baglary et al., 2025).

The anitimicrobial mechanisms of these natural compounds against bacteria are multifaceted. Essential oils and phenolic extracts exert their action by mainly breaking the membrane of the cells of the microorganism, resulting in leakage of the content of the cell and loss of viability (Noshirvani & Abolghasemi Fakhri, 2025). Additionally, they are able to disrupt the function of enzymes inside microorganisms, block metabolic processes and cause oxidative stress, which results in the prevention of microbial growth and prolonged product shelf life. Several studies have contributed towards proving the synergistic effect of combined essential oils or phenolic compounds for the enhanced antimicrobial effect even at lower concentrations (Ju et al., 2022; Nguyen & Karboune, 2023).

Despite their advantages, there are some challenges to such practical application of natural antimicrobials in bakery products. High concentrations necessary for microbial inhibition, therefore, may possess strong flavors or aromas that are undesirable to the consumer, hence changing the characteristic taste profile of the baked goods (Dong & Karboune, 2021). Moreover, there are interactions with other ingredients, pH, moisture content and also the baking processes which influence the stability and effectiveness of these compounds (Schefer et al., 2021). To overcome these drawbacks, methods such as encapsulation, nanoemulsion preterm delivery systems and controlled release systems are monitored and active compounds are slowly released while preserving the sensory and structural quality of bakery products (Ben-Fadhel et al., 2024).

Antioxidants

Lipid oxidation is one of the most important causes of bakery product degradation, especially bakery products with higher-fat and oil contents such as pastries, cookies, and enriched-breads (Holkovičová et al., 2025). Oxidative reaction contribute to the formation of rancid flavors, off-odors and decreased nutritional quality in the end product, impacting acceptance of food by the final consumer and shelf life (Xia et al., 2024). To counteract these effects, antioxidants, both natural and synthetic, are often included in the formulations used in bakeries in order to limit the development of the oxidative processes and preserve the sensory and nutritional quality on storage (Petcu et al., 2023). Natural antioxidants such as extracts from rosemary, green tea polyphenols, tocopherols, and ascorbic acid have become popular because of safety and health benefits and healthy-looking labels (Iqbal et al., 2024).

The primary mechanism of action of these compounds consists of free radical scavenging, inhibition of metal ion chelation, and in chain propagating reactions in lipids. Rosemary extract, for example, has shown to be effective in the delay of oxidation of the fat-rich bakery products, whereas the green tea catechins have other antimicrobial actions (Iqbal et al., 2024). The use of natural antioxidants is very much in line with current consumer trends for minimally processed foods and products without the use of synthetic chemicals (Rathee et al., 2023). Synthetic antioxidants include butylated hydroxyanisole and butylated hydroxytoluene and are very efficient in the prevention of lipid oxidation and are widely used in the bakery industry (BOUFTIRA, 2023). However, there are regulatory limits on their application in many areas because of health concerns at high concentrations, which has also provided further incentive to find alternatives that are natural in origin. In effect, a synergistic combination of the antioxidants, either natural and synthetic or multiple combinations of natural extracts can be used, giving the antioxidant better stability but lower dosages (Mapeka et al., 2022). Incorporation of antioxidants in bakery products therefore is a viable and effective approach to help preserve flavor, aroma, color and nutritional quality to prolonged shelf life and ultimately consumer satisfaction.

Enzymes

Enzymes are used in the formulations for bakeries as a natural and effective approach in order to retain freshness and prolong the staling process, thereby extending the shelf life (Kaur, 2024). Staling in baked products, especially in bread and cakes, comes mainly from starch retrogradation and alterations in structural organization of the product's crumb portion. Anti-staling enzymes, such as amylases, xylanases, as well as glucose oxidase act by changes in the starch and non-starch polysaccharides in the dough matrix, which slow retrogradation of starch and maintain crumb softness over time (Mohammadi-Moghaddam et al., 2024). By the specific biochemical pathways of these staling, these enzymes allow maintenance of textural quality without having negative influences on taste or appearance (Dai et al., 2024).

The amylases break down the starch molecules into smaller dextrins which retain moisture and softness to the crumb and the xylanases break down the hemicellulose, which enhances dough extensibility and gas retention (Zhou et al., 2025). Glucose oxidase on the other hand, modulates dough strength by catalyzing cross-linking reactions to improve dough stability and increase the volume of a loaf (Guo et al., 2023). The combination of these resulting from these enzymes results in terminological effects on baked products that result in softness, moisture and a longer perception of freshness. Enzymatic interventions may be adapted depending on the type of product, the baking conditions, and the intended extension of the shelf life, which provides flexibility for use in the industry (Lohita & Srijaya, 2024).

Beyond their role in texture, enzymes can also play an indirect role in microbial stability by keeping the environment less supportive to spoilage as well as showing synergism with other ingredients, such as emulsifiers, natural antimicrobials (Zhou et al., 2025). Importantly, enzymes are viewed as safe, naturally derived additives and can be used in the formulation of a clean-label bakery offering in line with overall consumer needs for products that are free from synthetic preservatives (Dong & Karboune, 2021). Their integration in the production of bakery items represents a targeted, efficient and sustainable approach to increase the shelf life while maintaining quality attributes which are essential for the acceptance of bakery by consumers.

Emulsifiers and Hydrocolloids

Emulsifiers and hydrocolloids are key functional ingredients within bakery products, and are used widely to help make the dough work harder, improve the texture of the product and prolong shelf life (Šmídová & Rysová, 2022). Emulsifiers such as mono-glycerides and diglycerides, DATEM (diacetyl tartaric acid esters of mono-glycerides and diglycerides), and SSL (sodium stearoyl lactylate) act basically by strengthening the gluten network and stabilizing the gas cells whilst also helping to improve the elasticity of the dough (Tebben et al., 2022). These effects are of special significance in bread products where gas retention has to be uniform to give a fine crumb structure, increased loaf volume and therefore a softer texture. By interacting with the starch molecules the emulsifiers also decrease the rate of retrogradation, slowing the crumb firming and also effectively delaying staling during storage (Zhang et al., 2025). Their incorporation enables the manufacturer to preserve a fresh mouthfeel and desirable softness for longer periods, which is very important to consumer acceptance and marketability.

Hydrocolloids including polysaccharides come in forms such as xanthan organic gum, guar gum, locust bean gum and cellulose derivatives and are responsible for the extension of shelf life TacCE majorly due to water retention and modulation of the structure or matrix of the dough (Petitjean & Isasi, 2022). These hydrocolloids form a gel-like network which acts to bind free water and reduce both moisture migration between crumb and crust, which will reduce both dryness and excessive softening. In addition, hydrocolloids interact with starch and gluten and improve the dough viscosity, elasticity and overall stability (Basit et al., 2025). This leads to better dough handling properties, uniform crumb structure and consistent loaf volume, while at the same time retarding staling and deterioration of texture. Hydrocolloids can also be useful in gluten-free products where gluten would otherwise have granted the product and its structural support (Sharanagat et al., 2022).

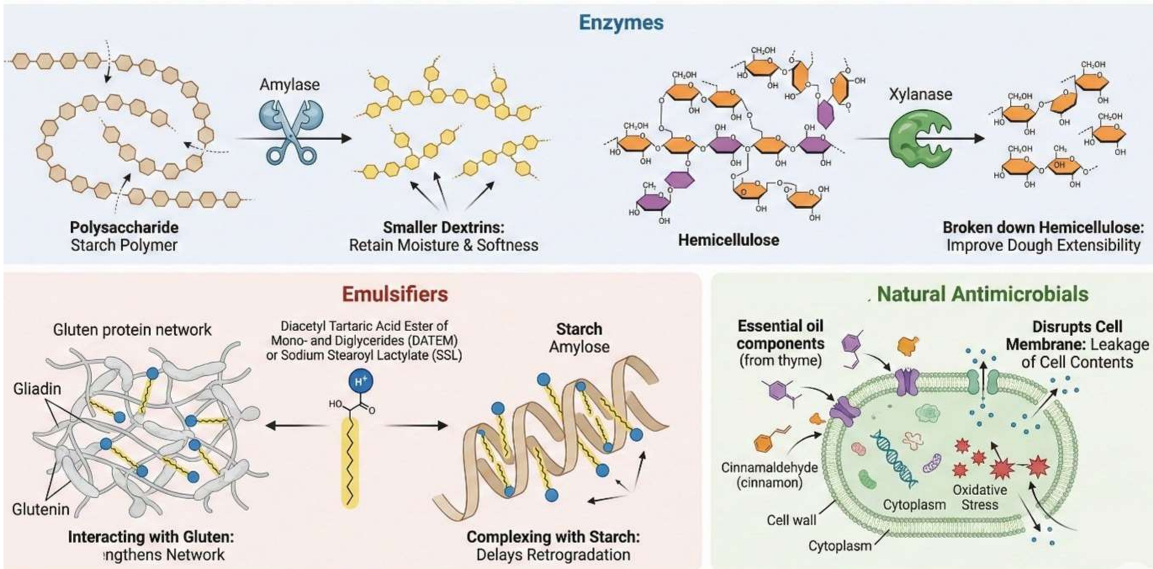

Fig.2: Biochemical mechanisms of clean-label formulation strategies (Santiesteban-López et al., 2022)

The combination of using emulsifiers and hydrocolloids have a synergistic effect and further enhance the textural as well as moisture-related stability (Mata et al., 2025). Emulsifiers, which help even out the distribution of fats and water, improve the crumb softness, hydrocolloids which help retain moisture and also delay the task of retrogression (Alam et al., 2025). This synergy is also important in aiding the usefulness of other strategies used to preserve food, such as those based on the use of enzymes, antioxidants, natural antimicrobials.

Use of Sourdough and Fermentation

Sourdough fermentation is a very old method that has steadily gained interest once again as a natural sustainable method for the shelf life of bakery products (Diowksz & Sadowska, 2021). The process is based on the metabolic activity of the lactic acid bacteria (LAB) and yeasts, which convert the fermentable sugars into organic acids, ethanol and carbon dioxide. Organic acids: Mostly lactic acid and acetic acid which act as natural preservative for dough by lowering pH value creating an environment that is inhibitory to spoilage microorganisms such as molds, yeasts and some bacteria (Alper & Altan, 2024; Pitt & Hocking, 2022). The antimicrobial action of sourdough fermentation not only delays the development of such microorganisms but also disturbs the use of synthetic preservatives, reaching the current consumer demand for clean label products in the bakery industry (Boudaoud et al., 2021).

In addition to their preservative effect, sourdough fermentation has a positive effect on the physicochemical and sensory properties of bakery products (Calabrese et al., 2022). The formation of organic acids and other metabolites affects the dough rheology and improves the extensibility, gas holding capacity and volume (De Vuyst et al., 2023). Furthermore, these acids react with the starch and gluten proteins modulating the crumb structure and moisture retaining ability. As a result, sourdough fermented breads have softer crumb texture, slower staling and longer freshness than conventional yeasted breads (Fu et al., 2024). The fermentation process also contributes to better flavor and aroma development so overall consumer acceptance can be increased and product stability ensured in storage.

The microbial or bio-chemical dynamics of sourdough means that it is especially useful for high moisture bakery products which are more susceptible to microbial spoilage. By preventing competition of acidification through microbial antagonism combined with the species in sourdough culture assist prevent competitions of multiplied parasite linguistic interest spoilage to grow and maintain increased quality structures (Wang & Wang, 2024; Xing et al., 2021). New methods that combine sourdough with other preservation methods like enzymes, hydrocolloids or natural antimicrobials are often used today to create a synergy effect and further increase shelf life (Lohita & Srijaya, 2024).

Critical comparison of formulation based strategies

Formulation-based strategies for extending shelf life vary considerably in terms of their effectiveness, sensory influences and acceptance at the regulatory level. Natural antimicrobials have lot of clean-label qualities but short cut on the flavor at performance levels, but synthetic preservatives have predictable effects on the microbial activity with consumer hatred (Teshome et al., 2022). Enzymes are effective in retarding staling, without resulting in sensory penalties, and hydrocolloids improve the moisture retention in the product but may change the crumb structure if used in excess (Kaur, 2024). Fermentation based approaches such as sourdough offer multifunctional benefits and even create process complexity in order to deliver reproducibility (Wang & Wang, 2024). Therefore, formulation strategies need to be chosen on the basis of balance between shelf life efficacy, sensory quality and clean-label compatibility.

Table 3: Comparative overview of formulation-based Shelf life extension tools (Petcu et al., 2023)

Lever	Primary benefit	Clean-label fit	Expression	References
Natural antimicrobials (essential oils, phenolics, organic acids)	Mold delay	High	High-moisture products needing label appeal	(Nguyen & Karboune, 2023)
Antioxidants (rosemary, tocopherols, ascorbic acid; BHA/BHT where allowed)	Oxidation control	Medium to high	Fat-rich baked goods	(Petcu et al., 2023)
Anti-staling enzymes (amylase, xylanase, glucose oxidase)	Softness retention	High	Bread, cakes, soft rolls	(Mohammadi-Moghaddam et al., 2024)
Emulsifiers (DATEM, SSL, mono- and diglycerides)	Structure plus slower staling	Medium	High-volume bread systems	(Tebben et al., 2022)
Hydrocolloids (xanthan, guar, cellulose derivatives)	Moisture retention plus texture	High	Gluten-free, reduced-gluten, cakes	(Zhang et al., 2025)
Sourdough fermentation	Microbial stability plus sensory and texture	Very high	Artisan and premium breads	(Wang & Wang, 2024)

Processing and Technological Interventions

Technological interventions for processing baked goods bring in the pivotal role in product shelf life extension holding onto quality and safety. Beyond the ingredient based approach, intervention in the process and innovative use of advanced technologies is very widespread in modern bakery operation to manage microbial growth, staling and chemical degradation (Awasthi et al., 2025; Noshirvani & Abolghasemi Fakhri, 2025). These interventions consist of modified baking processes, hurdle technology, and novel thermal and non-thermal treatments which have their own advantages in extending the shelf life and improving consumer acceptability (Taglieri et al., 2021). In practice, their efficiency relies on the well control of the critical parameters such as temperature vs time profiles, cooling rate, the sanitation, and the post-bake handling which profoundly determine the recontamination risk as well as moisture dynamics. When combined with the appropriate packaging, process-based interventions can be used to stabilize the micro-environment in the packaging, slowing the rate of oxidation and limiting quality losses driven by oxygen and humidity (Qu et al., 2022). Importantly, the feasibility of these technologies is influenced by industrial constraints such as cost of equipment, integration into a line, throughput and regulatory compliance. Consequently, to select the best way for the products to be processed, product specific validation will be needed to strike the best balance between increased shelf life and sensory quality expectations with clean label (Santiesteban-López et al., 2022).

Modified Baking Processes

Modified baking processes are technology interventions that are broadly implemented in order to increase the shelf life of products produced in bakeries by controlling microbial load and reducing the rate of quality deterioration (Sowmya & Ramalingappa, 2025). Techniques, including partial baking, vacuum cooling and partial baking have been developed which optimize the baking process while maintaining product freshness, texture and safety. These techniques not only give operational flexibility for industrial bakeries, but enable better storage, transport, and retail distribution of baked goods without a negative impact on consumer acceptability (Kothari et al., 2024). Partial baking is an intermediate baking process, in which products are baked in a structurally set but not fully cooked stage. This technology decreases the microbial load, as well as, minimizes moisture movements and increases shelf life during storage and transportation (Vermelho et al., 2024). Partial baked goods are ready after final baking before making their way to the consumer while maintaining freshly baked characteristics and remaining safe. This technique works especially well for breads and pastries that are high in moisture content and thus conventional baking may not be able to control any spoilage and staling during long storage periods (Kaur, 2024; Owusu-Apenten & Vieira, 2023).

An innovative technique, vacuum cooling, also increases the shelf life of products by rapidly reducing product temperatures at low pressures. This process inhibits the growth of microorganisms, prevents staling and stabilizes the structure of this product, especially for high moisture products (Dirapan et al., 2021). By helping to reduce condensation and accumulation of moisture, vacuum cooling helps to reduce mold formation during storage. Combined with optimized baking schedules such as shorter baking times and lower temperatures, means that it is possible to create bakery products that will maintain freshness, texture, and safety longer without resorting to chemical preservatives (Alp & Bulantekin, 2021). Overall, baking process modifications such as partial baking and vacuum cooling are a promising solution to the problem of increasing the shelf life, sensory qualities, and safety of bakery products. These techniques, when combined with other techniques such as natural antimicrobial, enzymes or advanced packaging, facilitate the manufacture of bakery goods that satisfy the consumers demands for freshness, safety, and convenience (Santiesteban-López et al., 2022; Zhou et al., 2025).

Hurdle Technology

Hurdle technology is a very popular form of preservation that increases the shelf life of bakery products by using a combination of several inhibitory factors, or hurdles, to control microbial growth and retard quality decline (Ranjitha, 2021). Unlike the single-strategy methods of preservation, the hurdle technology combines complementary methods such as pH control, use of preservatives, reduction of moisture, and suitable packaging (Kępka-Borkowska et al., 2025). The combined impact of these barriers creates an ecosystem that is poor for the existence of spoilage creatures, whilst reducing the impacts on taste, remembering, and all-round appeal to the consumer product.

pH control is an important problem in preservation of bakery products. Acidification by organic acids or sourdough fermentation causes a lowering of pH and will inhibit the growth of molds, yeasts, and some bacteria (Sowmya & Ramalingappa, 2025). Chemical and natural preservatives, such as calcium propionate, sorbic acid and antimicrobials derived from certain plants, also have a function in limiting microbial growth. Reducing water activity by formulating ingredients, partial dehydration or the use of sugar and salt reduces the availability of free water required for the microbial metabolism (Alp & Bulantekin, 2021; Bensid et al., 2022). While each single hurdle may not be completely effective in preventing spoilage, the combination of many of them may have a synergistic effect that contributes to increased microbial stability and the preservation of product quality.

Packaging plays a vital role in this integrated approach of preservation practice because it minimizes oxidative reactions, moisture migration and environmental contamination (Chou et al., 2023). Used in conjunction with controlled pH, preservatives, and lowered water activity, packaging is useful to help preserve the textural and sensory integrity and microbial integrity of bakery products during storage. Hurdle technology has proven to work very well for high-moisture bakery products, like bread, cakes and cream-filled pastry, in which single interventions may not be enough to extend shelf life (Ranjitha, 2021; Teshome et al., 2022). By applying numerous different preservation techniques hurdle technology allows manufacturers to produce safe, stable and good quality bakery products with a low use of synthetic additives.

Hurdle technology is used to offer a uniting framework for bakery preservation by combining formulation, processing and packaging interventions. Rather than single preservation tool, combined effect of moderate hurdle like pH control, reduction of water activity, antimicrobial and reduction of oxygen limitation facilitate successful shelf life extension whilst maintaining sensory quality and compatibility with clean label.

Table 4: Hurdle technology elements applied in bakery preservation (Gupta, 2024)

Hurdle component	Targeted deterioration	Common tools	Key considerations
pH reduction	Mold and yeast growth	Sourdough, organic acids	Flavor balance
Water activity control	Microbial growth, texture loss	Humectants, hydrocolloids	Overuse risks
Antimicrobial action	Spoilage organisms	Natural preservatives	Regulatory limits
Oxygen limitation	Oxidation, aerobic molds	MAP, scavengers	Seal integrity
Process hygiene	Recontamination	Rapid cooling, sanitation	Operational discipline

Novel Thermal and Non-Thermal Technologies

Recent progress in thermal and non-thermal processing technologies has brought about a revolution in the preservation of bakery products and provide innovative solutions to prolong the shelf life of bakery products without compromising their quality (Lohita & Srijaya, 2024). Conventional thermal treatments, such as baking for several days, and pasteurization are effective to ensure that the growth of spoilage microorganisms is controlled, but tend to negatively impact texture, flavor, and nutritional value, particularly of heat resistant microorganisms. In contrast, the use of novel technologies can offer targeted microbial control as well as a lack of excess heat and sensory characteristics and structure preservation, especially with high moisture or delicate bakery products, where traditional processes can be insufficient (Dong & Karboune, 2021; Lohita & Srijaya, 2024).

High-pressure processing (HPP) and microwave stabilization are interesting technologies for the preservation of bakery products. HPP utilizes high hydrostatic pressure (deactivation of spoilage microorganisms and enzymes) to maintain the texture, odor and nutritional values of products. It is especially good for cream-filled breads, cakes and pastries (Sojecka et al., 2024). Microwave stabilization can provide even heating, both over time and throughout the product, that reduces microbial load, moisture content, making the crumb softer, tastier and the product more appealing that makes it a good candidate with lengthy shelf life without the need of chemical preservatives (Nguyen & Songsermpong, 2022).

Emerging non-thermal technologies such as UV-C irradiation, cold plasma, ionizing irradiation and ultrasound increases shelf life as well. UV-C and cold plasma destroy the microbial cell membranes and the microbial enzymes and are therefore suitable for decontaminating the crusts of bread, cookies and pastries (Chiozzi et al., 2022). Ultrasound treatments increases heat transfer, microbial structure collapse and modification of the dough composition; helps to retain moisture and delay staling. When used in combination with traditional interventions of baking, packaging or ingredients, these technologies have synergistic effects, ensuring food safety, microbial stability and prolonging freshness (Jadhav et al., 2021; Nguyen & Songsermpong, 2022). Together, these novel processing methods provide versatile, efficient and sustainable solutions for the bakery industry.

Comparison of processing interventions

Conventional thermal processing is still effective to reduce the microbes, but commonly leads to a loss of texture and flavor, especially for high moisture bakery products. In contrast to that, non-thermal technologies, including high-pressure processing, UV-C, cold plasma offer targeted microbial control with limited thermal damage levels in terms of cost balance and the availability of equipment (Chiozzi et al., 2022). Moreover, intensive processing may have a negative effect on dough structure and sensory characteristics. Consequently, processing technologies should be optimized as minor interventions and combined with formulation and packaging concerns as the method of achieving commercially viable shelf life extension (Thakur et al., 2022).

Packaging Solutions for Shelf life Extension

Packaging has a crucial role to play in quality, safety and shelf life of bakery products. Beyond the physical protection they provide, modern packaging systems are intended to regulate a variety of environmental factors such as moisture, oxygen, and microbial contamination as well as interact with the food to maintain sensory and nutritional properties (Chiozzi et al., 2022; Ribeiro et al., 2021). Adavances in packaging technologies, including conventional materials, modified atmospheres, active and smart packaging and edible coatings have made it possible to achieve significant improvements in product stability, reducing food waste and increasing consumer acceptability.

Conventional Packaging Materials

Conventional packaging materials are very important to prolong the shelf life of bakery products by offering a physical barrier against environmental factors responsible for staling, moisture loss and microbial spoilage (Noshirvani & Abolghasemi Fakhri, 2025). Low-density polyethylene has a large application in bakery packaging thanks to the combination of its flexibility, heat-sealing abilities and moisture barrier properties, which will keep crumb levels soft, avoiding drying out (San et al., 2022). Its transparency is also helpful in the evaluation of consumer products. However, the moderate level of oxygen permeability of Low-density polyethylene can cause oxidative rancidity and mold development of fat-rich and high moisture products, requiring the complement of other food preservation techniques (Moll & Chiralt, 2025).

Polypropylene is another common polymer used in package solutions for the bakery industry and is preferred for its high mechanical strength, resistance to chemicals and ability to withstand high temperatures (San et al., 2022). Polypropylene is especially ideal for use in heat treated products such as partial baked breads or frozen dough because it gives the product dimensional stability during storage and helps limit the chance of contamination. Like low-density polyethylene, polypropylene moderate oxygen permeability may necessitate combining it with other preservation techniques, such as vacuum or modified atmosphere packaging, where the extended shelf life needs are concerned (Habiba et al., 2025). All in all, conventional and high performance packaging materials play a basic role in the preservation of baked goods, balancing the three factors of chance of moisture retention, structural integrity, and protection from environmental contaminating agents (Vermelho et al., 2024). These materials constitute the foundation for the integration of the new advanced packaging technologies to further improve shelf life and product quality.

Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging (MAP) is a technology popularized in the market for prolonged shelf life using the changing gas composition of the package internal atmosphere for bakery products (Habiba et al., 2025). Unlike defined packaging support of rivers, which relies on the physical barrier, only change levels of oxygen and rises inert or antimicrobial gases such as carbon dioxide and nitrogen. Carbon dioxide is an effective gas agent in preventing and restraining the growth of aerobic spoilage organisms, such as molds and yeasts, by interfering with post-metabolic functions (Awulachew, 2024). Being inert, it also gives it the ability not to oxidize and conserve volatile compounds such as flavors, aromas that are sensitive to oxidation by oxygen. MAP efficiency is product dependent, with elements such as moisture content, fat composition and its surface structure affecting the permeability of gas and microbial susceptibility to MAP (Habiba et al., 2025). For high-moisture products, such as bread and cream filled pastries, MAP decreases mold growth while for fat-rich products, such as cakes and cookies, MAP reduces lipid oxidation (Alp & Bulantekin, 2021). Studies endorse that CO_2-enriched atmospheres will decelerate mold build up from days to a number of weeks depending on the concentration and storage situation.

In addition to the microbial control, MAP is also useful in maintaining physical and textural quality as it can help prevent oxidative rancidity and fluctuation of moisture in the food causing staling (Kaur, 2024). MAP can be used together with other preservation skills such as natural antimicrobials or modified baking procedures, to extend the shelf life and the product safety. Advances in MAP technology mean that precise control over the composition of the gases used, package sealing and permeability is possible, enabling manufacturers to customize packaging to individual product requirements (Nguyen & Songsermpong, 2022; Ribeiro et al., 2021). Overall, MAP is a versatile and effective packaging solution to microbial control, oxidation control, and moisture control making it a key part in modern bakery shelf life extension.

Active Packaging

Active packaging represents a sophisticated approach that goes beyond passive containment, proactively influencing the internal environment to enhance food quality, safety, and shelf life (Kadirvel et al., 2025). A major advancement in this field is antimicrobial packaging, which incorporates antimicrobial agents directly into packaging materials to control the growth of spoilage and pathogenic microorganisms. Essential-oil-infused films containing bioactive compounds such as thymol, eugenol, carvacrol, and cinnamaldehyde are gaining attention due to their natural origin, potent antimicrobial properties, and consumer acceptance (Fadiji et al., 2023). These compounds migrate from the packaging matrix to the food surface, disrupting microbial membranes and inhibiting enzymatic activity. Nanotechnology-based systems, particularly those using silver nanoparticles, zinc oxide, chitosan nanoparticles, or nano-clays, offer enhanced antimicrobial effects due to their high surface area to volume ratio, rapidly destroying microbial cells and providing long-lasting stability (Singh et al., 2024).

Another key component of active packaging is oxygen scavenging, which maintains a low oxygen environment to prevent oxidative degradation, pigment discoloration, and the growth of aerobic microorganisms (Gupta, 2024). Oxygen scavengers, often composed of iron based powders, ascorbic acid, or enzymes, effectively remove residual oxygen in the package, preserving the sensory qualities of color and aroma-sensitive foods, and inhibiting lipid oxidation in high-fat products (Kordjazi & Ajji, 2022). Moisture management is also critical in active packaging, especially for bakery products, dehydrated foods, and powdered formulations. Moisture absorbing systems, such as silica gel, calcium chloride, starch based polymers, and superabsorbent hydrogels, prevent spoilage by absorbing excess water vapor, which can lead to microbial growth, caking, or deterioration of texture (Nugrahedi et al., 2025). Together, these active packaging technologies establish a controlled microenvironment within the package, minimizing biochemical, microbial, and physical deterioration during storage and distribution. By combining antimicrobial agents, oxygen scavengers, and moisture absorbers, active packaging provides a comprehensive preservation strategy that aligns with industry trends toward clean-label solutions, reduced food waste, and sustainable packaging innovation (Jagarlamudi, 2022; Ribeiro et al., 2021).

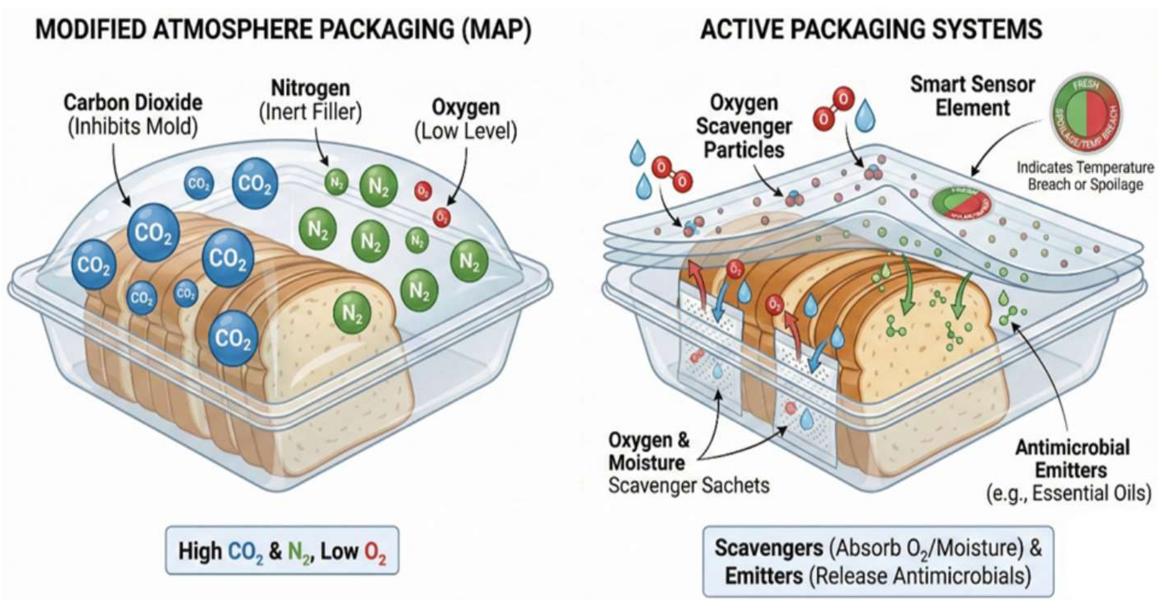

Fig.3: Comparison of packaging interventions (Moll & Chiralt, 2025; Qu et al., 2022)

Clean-Label Shelf life Extension Approaches

Clean-label shelf life extension approaches have attracted large attention in response to increasing consumer demand for the natural, recognizable and minimally processed food (Santiesteban-López et al., 2022). This trend has led the food industry to look for alternatives to synthetic preservatives such as sorbates, benzoates, and nitrites, choosing preservatives that have a safer and more natural image and a transparency of origin. Clean-label preservation targets plant-based compounds, microbial metabolites, and enzymatic systems in order to keep them fresh without the use of artificial additives (Chauhan & Rao, 2024; Cheng et al., 2022). This shift is due to a greater consumer perception of ingredient lists and the possible health consequences of synthetic chemicals, and it goes hand in hand with the general trend towards more healthful and sustainable food products.

To cover this demand, researchers and manufacturers are developing clean-label antimicrobials and enzymes with antimicrobial, antioxidant and textural stabilizing properties (Cheng et al., 2022). Natural antimicrobials including essential oils, plant extracts with high phenolics, organic acid and fermented plant derivatives, have good antimicrobial and antifungal effects and are also flavor and functional ingredients (Petcu et al., 2023). Biopreservatives such as bacteriocins (e.g. nisin), protective cultures and probiotic strains are more and more used for spoilage microorganisms inhibition by the competitive exclusion and the production of antimicrobial metabolites (Mokoena et al., 2021). Enzymatic systems, for example, glucose oxidase, catalase and enzymes based on amylase, are clean-label solutions controlling oxidation, increasing the microbial stability of foods and the storage life of food products without impairing nutritional values (Chauhan & Rao, 2024). Clean-label strategies bridge the gap between technological innovation and consumer desires for natural and transparent ingredients in order to develop safe and high-quality foods with longer shelf life to meet the increasing demand for healthier, sustainable foods.

Table 5: Packaging strategies for shelf life extension of bakery products (Chiozzi et al., 2022; Nugrahedi et al., 2025)

Packaging system	Controlled factor	Main benefit	Industrial maturity
Moisture-barrier films	Moisture loss	Slower staling	High
High-barrier multilayers	Oxygen and moisture	Reduced oxidation	High
Modified atmosphere packaging	Headspace gases	Mold delay	Very high
Active packaging	Oxygen, surface microbes	Extended Shelf-life	Medium–High
Edible coatings	Surface protection	Clean-label appeal	Medium
Smart packaging	Quality monitoring	Waste reduction	Emerging

Critical comparison of packaging strategies

Packaging strategies vary greatly in their effectiveness for the control of microbial growth, water migration, and oxidative reactions. Modified atmosphere packaging is an effective means of delaying mold growth however is very dependent on gas composition and package integrity. Active packaging involves giving added protection through compounds with antimicrobial properties or ability to scavenge but the disadvantage is the control over release and the need for regulatory approval. While biodegradable and edible packaging materials help us to become sustainable, they tend to have inferior barrier properties than conventional polymers. Therefore, packaging selection involves a trade-off between the performance of the shelf life and sustainability and feasibility from industrial point of view.

Shelf life Evaluation Techniques

Accurate evaluation of food product shelf life is important for managing the stability, safety and quality of food products on storage. A comprehensive shelf life assessment generally involves the combined use of microbial, physicochemical, sensory as well as predictive modelling approaches in order to produce a holistic understanding of product deterioration (Ablegue et al., 2025). Such used concomitant methods can assist in determining the key pathways of spoilage, support preservation practices in order to be scientifically supported and prove presumed shelf life statements (Lohita & Srijaya, 2024).

Microbial Testing

Microbial testing is considered to be a very critical part of shelf life testing since in most cases microbial growth is taken to be the quality threshold that defines spoilage, and safety limit is reached for food products (Tarlak, 2023). Total mold count as well as yeast count are commonly performed in order to quantify the presence of common spoilage organisms that can survive under usual storage and distribution accidents, especially in bakery products, confectionery and high moisture content food products (Alp & Bulantekin, 2021). These analyses include serial dilutions and plating onto selective media such as potato dextrose agar or yeast extract glucose agar and incubation to obtain the colonies-forming units (CFU) per gram.

Monitoring of mold and yeast populations over time is useful to identify the rate of fungal contamination, detect early spoilage, and determine the success of any antifungal intervention i.e. the preservatives or active packaging systems (Chou et al., 2023; Taglieri et al., 2021). In addition to natural monitoring of microorganisms, during such studies, products are also inoculated with known spoilage organisms or food pathogens such as *Aspergillus*, *Penicillium*, *Saccharomyces*, or *Listeria* species to deliberately introduce certain microbial contaminants into product intended to be stored, to evaluate the behavior of these crucial microorganisms under controlled conditions (Piotrowska et al., 2024). Recent studies give critical information on microbial growth rates, survival patterns and resistance to storage strategies and, ultimately, allow manufacturers to validate safety margins and make secure claims for shelf life (Cheng et al., 2022). The collective compiled microbial analyses makes the basis of being knowledgeable on the processes of food spoilage and maximizing provisions preservation regimens.

Physicochemical Analysis

Physicochemical analysis supplies the required quantitative information on the change in food quality during storage hence it constitutes a major part of any shelf life study. Moisture content which is measured using oven drying, vacuum drying, or Karl Fischer titration is important as slight changes can have a significant effect on microbial development, texture, and staling behavior (Braham et al., 2022). Water activity assessed members using hygrometers and dew-point water activity meters are employed to determine availability of free water of support for biochemical reactions and microbial proliferation (Cheng, 2024). Water activity checking and control of microorganisms. The maintenance of water activity maintaining many bakery products and intermediate moisture food products at less than the critical declared water activity is of vital importance to prevent spoilage (Noshirvani & Abolghasemi Fakhri, 2025). Textural degradation is monitored applying Texture Profile Analysis (TPA), an instrumental technique based on measuring textural parameters like hardness, cohesiveness, springiness and chewiness, for which food samples are compressed in order to simulate chewing (Scott & Awika, 2023). TPA result helps by tracking the loss of firmness, hardening of crumbs or the softening; which is often due to staling, moisture migration or breakdown of the structure.

Color stability is analyzed with the use of colorimeters or spectrophotometers using the CIE Lab system giving insights on the browning reactions, decay of pigments and oxidation reactions which in turn affects the appearance of the product over time. Oxidative spoilage is assessed by measuring lipid oxidation, which may be measured as thiobarbituric acid reactive substances parts of which are malondialdehyde and other secondary oxidation products that give rise to rancid odours and off-flavours (Xia et al., 2024). These physicochemical parameters, when evaluated together, can help to obtain an image of the deterioration mechanisms and help to create specific strategies to successfully extend shelf life and optimize product quality.

Sensory Evaluation

Sensory evaluation is an essential part of the shelf life evaluation process because it measures the changes in food quality that are perceived by the consumer that cannot be fully detected by the use of instrumental determination processes. Trained sensory panels or consumer testers are used in a systematic way to evaluate important attributes such as freshness, which includes overall appearance, aroma and flavor characteristics that diminish as the product changes biochemically and microbially after storage (Sipos et al., 2021). Assessments of texture changes are nevertheless of particular importance for products susceptible to staling, moisture migration or breakdown of their structure; firmness, softness, chewiness and crumb structure are evaluated by the panelists to determine at what point textural changes can be seen or perceived as unacceptable to consumers (Mohammadi-Moghaddam et al., 2024). In addition, sensory panels are used to monitor the formation of off-flavors, such as rancid, sour, yeasty or cardboard-like flavors which are a result of lipid oxidation, microbial metabolism or chemical reaction. These slight changes in taste often will be early indicators of a loss of quality even before instrumental measurements can detect significant deviations from quality (Machado et al., 2023). Sensory evaluation therefore aids in providing critical qualitative and quantitative data to complement microbial and physicochemical analyses that aid in defining the practical end point of shelf life based on consumer acceptability and not entirely on analytical criteria (Noshirvani & Abolghasemi Fakhri, 2025). Through this integrated approach, manufacturers will be better able to understand the viability of a product, how to optimize formulation strategies and how to ensure that the product will have the same sensory quality throughout the intended storage period.

Shortcomings of current methods of evaluating Shelf life

Current methods for evaluating shelf life often use microbial endpoints as an indication of quality loss that may not absolutely reflect consumer perception of quality loss. Sensory rejection often precedes microbiological spoilage of foods, especially the result of stalling or the worsening of flavors (Mollakhalili-meybodi et al., 2023). Accelerated storage studies are useful for giving quick information yet may not simulate real-time mechanisms of deterioration very well. Furthermore, the absence of standardized protocols for testing and make them uncreditable of comparing across studies (Cheng, 2024). The faults in this are critical that have to be tackled in order to be able to provide good and relevant predictions of the shelf life.

Recent Advances and Future Trends

Recent developments in food packaging, however, have moved from simple containment systems to more sophisticated, active and intelligent packaging systems, which have enhanced both quality of food and sustainability of the environment. Key technologies in food preservation are nanotechnology, natural preservative encapsulation, artificial intelligence for monitoring, and sustainable materials are changing food preservation and the management of food supply chains. These innovations are not only good for food safety and shelf life, but they are also good for the environment. Nanotechnology role in food packaging is to a great extent managing materials at the molecular level. Nanocomposite film using the method of throwing nanoparticles into polymers to form films, the performance of some parts, such as the improvement of film mechanical strength performance, thermal resistance and gas barrier performance, will be better than ordinary plastics. The introduction of antimicrobial nanoparticles, such as silver or zinc oxide helps to inhibit the growth of spoilage micro-organisms, extending the shelf life and improving the safety and reducing the post-harvest losses of food.

The demand for clean label foods brought natural preservatives, such as essential oils and antimicrobial peptides, in the place of chemicals. However, their volatility, susceptibility to degradation and intense tastes may restrict their direct application. Encapsulation techniques such as microencapsulation, nanoemulsions and liposomes have been addressed as effective solutions by providing stability to these compounds, controlling release and improving solubility and bioavailability. Encapsulated antibiotics, like essential oils carried as biodegradable polymers, release over periods of time and provide the greatest benefit in terms of that they maintain the sensory qualities and prolong storage life. Smart packaging using internet of things can read sensors for real-time data such as temperature, humidity and gas composition and alert manufacturers, distributors and consumers.

Sustainability is a motivational element in food packaging with growing awareness on environmental impact. Biodegradable films based on renewable polymers such as polylactic acid (PLA), starch blends and chitosan have been replacing the petroleum-based plastics with the same or similar barriers and thermal characteristics. Material science advance has allowed the use of natural fillers such as nanocellulose and the use of antioxidants in order to improve material functional performance, while contributing to circular economy manifestations. Sustainable packaging is in line with consumers expectations of eco-friendly products and corporate social responsibility targets. Despite improvements in technology, however, consumers must trust the technology and must also comply with regulations in order to see its widespread adoption. Regulatory bodies are attempting to come up with guidelines so that these innovations achieve high safety and efficacy. Standardized protocols for the testing, labeling rules and international harmonization are crucial for their large-scale implementation.

Finally, compatibility between preservation strategies is also a practical challenge. Interactions between the formulation components and processing and packaging systems for microbial stability, texture and performance on shelf life can be non-additive effects. For example, heat sensitivity of encapsulated bioactive, moisture redistribution in storage or mismatches of permeability in packaging to the bioactive can minimize the effectiveness of otherwise promising interventions. These limitations underscore the need for optimizing and integrated design approaches for different products, such as hurdle technology, to secure reliable and scalable shelf life extension for these products without compromising quality.

Despite promising laboratory-scale results, many shelf life extension strategies face challenges during industrial implementation due to cost, scalability, and regulatory constraints. Clean-label formulations often struggle to achieve shelf life robustness comparable to conventional preservatives, while advanced processing and packaging technologies raise sustainability and economic concerns. Future research should prioritize integrative, product-specific preservation systems that balance technological effectiveness, sensory quality, environmental impact, and regulatory compliance. Such holistic approaches are critical for translating scientific innovation into commercially viable bakery preservation solutions.

CONCLUSION

Bakery products are naturally susceptible to very rapid deterioration in quality because of the simultaneous effect of several spoilage mechanisms which occur in storage. Staling, which is mainly caused by starch retrogradation and wastage of moisture between crumb and crust and reduces softness and freshness progressively, even without controlling the microbial growth. At the same time, a large number of bakery goods, especially products with a high moisture content, fillings, or enriched formulations are very prone to mold and yeast growth on the other hand due to the favorable water activity and contamination after baking. In products that contain fat, lipid oxidation further degrades quality by the development of rancid off-flavors, aroma loss, discoloration and nutritional degradation. The collective evidence that has been reviewed in this work shows that bakery shelf life is seldom determined by a single process of deterioration but is governed by the interaction of microbial, physicochemical and environmental processes. Consequently, preservation strategies based on a single mechanism will not likely provide robust and commercially reliable strategies for Shelf life extension for a variety of bakery systems.

The most effective ways to prolong the shelf life for bakery products therefore depend upon integrated strategies for preservation feeding on multiple aspects of microbial stability, textural integrity and chemical stability simultaneously addressed and compatible with industrial processing and sensory aspirations. Formulation-based intervention creates a flexible base for such integrated systems. Natural antimicrobials, such as essential oils and phenolic-rich plant extracts and organic acids, show high antifungal and antibacterial effects against frequently occurring bacterial and fungal bakery spoilage organisms and may provide interesting alternatives to chemical preservatives. However, their potential use in practice needs careful optimization of dose to balance antimicrobial efficacy and sensory acceptability. Antioxidant systems both natural, such as tocopherols, rosemary extract, polyphenols, and synthetic where allowed are currently indispensable in regulation of oxidative deterioration of the fat-rich bakery products. Anti-staling enzymes like amylases, xylanases and glucose oxidase have been shown to play a crucial role in the modulation of starch retrogradation and dough structure which can result in prolonged softness and freshness, almost the sole determinant for a couple of days in terms of the consumers perception. Emulsifiers and hydrocolloids also pick up where moisture retention and cell structure stabilization of gases or emulsifiers have additional effects for additional moisture retention and moderation of moisture migration during the storage process. Fermentation-based approaches, specifically the sourdough systems, which include mainly lactic acid bacteria, can offer a multifunctional preservation tool by lowering the pH, by the inhibition of spoilage microorganisms and by the simultaneous improvement of the crumb structure, flavor development and moisture retention.

Processing based interventions amplify these formulation gains by reduced microbial load, moisture dynamics and enhancement of the distribution flexibility. Modified baking strategies, i.e. partial baking (par-baking) and optimized cooling, including vacuum cooling contribute to an improved microbial control and reduced microbial related spoilage by condensation and allow finish-baking closer to the point of sale. Hurdle technology emerges from this review as a uniting figure of preservation for bakery application integrating moderate levels of but complementary hurdles e.g. pH control, water activity modulation, antimicrobial protection and oxygen limitation, and hygienic processing. Rather than deploying extreme individual interventions, it is possible to use the combination of these hurdles to provide synchronized shelf life extension with a preservation of sensory quality and clean-label compatibility. Emerging technologies such as non-thermal and advanced processing technologies, such as high-pressure processing, UV-C irradiation, cold plasma, irradiation and ultrasound are additional tools for microbial control with minimal thermal processing within certain products such as high moisture or delicate bakery products where normal heat processing methods may be inadequate.

Packaging is the third fundamental element of shelf life design process and is more and more becoming an active part of preservation than being a passive barrier. Conventional polymer films and multilayer materials are still critical in controlling moisture and oxygen transfer and therefore have a significant impact on staling and oxidative reactions.

Modified atmosphere packaging technology has been evaluated to be very effective to delay mold growth and minimize the rate of oxidative deterioration, especially in bakery products that are packaged and high in moisture. Active packaging systems that make use of oxygen scavengers, moisture regulators and antimicrobial elements more precisely control the microenvironment of the packaging environment and direct surface contamination, the most common place where spoilage takes hold. Overall, this review emphasizes how successful shelf life extension in bakery products is achieved using a coordinated approach of formulation, processing, and packaging strategies using the hurdle technology approach.

Authors' Contribution: Sawera Hayat: Conceptualization, Investigation, Writing – original draft, Wali Ullah, adnd Saleha Tariq, Writing – review & editing. Izza Razzaq and Alisha: Visualization, Writing – review & editing.

Funding: This study was not supported by any public, commercial, or non-profit funding agency.

Conflicts of Interest: The authors declare no conflict of interest.

Generative AI Statements: The authors confirm that no generative artificial intelligence–based tools were employed in the conception, writing, editing, or preparation of this manuscript. All intellectual content, interpretations, and conclusions are the sole responsibility of the authors.

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