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Review article

Enhancing safety and quality in the global cheese industry: A review of innovative preservation techniques

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ABSTRACT

The global cheese industry faces challenges in adopting new preservation methods due to microbiological decay and health risks associated with chemical preservatives. Ensuring the safety and quality control of hard and semi-hard cheeses is crucial given their prolonged maturation and storage. Researchers are urged to create cheese products emphasizing safety, minimal processing, eco-labels, and clean labels to address consumer health and environmental worries. This review aims to explore effective strategies for ensuring the safety and quality of ripened cheeses, covering traditional techniques like aging, maturation, and salting, along with innovative methods such as modified and vacuum packaging, high-pressure processing, and active and intelligent packaging. Additionally, sustainable cheese preservation approaches, their impact on shelf life extension, and the physiochemical and quality attributes post-preservation are all analyzed. Overall, the cheese industry stands to benefit from this evaluation through enhanced market value, increased consumer satisfaction, and better environmental sustainability.The integration of novel preservation techniques in the cheese industry not only addresses current challenges but also paves the way for a more sustainable and consumer-oriented approach. By continually refining and implementing safety measures, quality control processes, and environmentally friendly practices, cheese producers can meet evolving consumer demands while ensuring the longevity and integrity of their products. Through a concerted effort to embrace innovation and adapt to changing market dynamics, the global cheese industry is poised to thrive in a competitive landscape where safety, quality, and sustainability are paramount.

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1. Introduction

Cheese is a nutritious and versatile dairy food manufactured from buffalo, cow, goat, and sheep milk. It is estimated that more than 500 distinct cheese varieties are currently produced worldwide [1]. Cheese-makers strive to maintain consistent and uniform raw material quality in cheese production [2]. Yield, flavour, texture and appearance of fresh cheese is influenced by many factors such as milk composition, seasonal and dietary variations in milk consistency [3]. Therefore, raw milk collection, addition of coagulating enzymes, coagulum formation and curd formation are among the key steps involved in making fresh cheese. The curd can be utilized to produce different types of cheeses [4].

The safety and quality of semi-hard cheeses as well as hard cheeses depend on how they are preserved. Several approaches are available for meeting this goal. For example, traditional methods like cooling can be used to make cheese last longer while maintaining its taste [5]. Another crucial aspect is controlling the growth of microorganisms because they have the ability to affect the standard and safety of cheeses. The aim of conservation methods is to decrease the development of spoilage organisms and kill the hazardous ones at the same time not interfering with lactic acid bacteria which give the cheese its final properties [6]. Moreover, the use of lactic acid bacteria (LAB) probiotics to modulate intestinal bacteria symbiosis may serve to enhance cheese fermentation and safety [7]. Moreover, the environment should also be considered when choosing food preservation techniques along the supply chain to ensure the quality and safety of hard and semi-hard cheeses it is necessary to critically evaluate methods of preservation. During their manufacturing sensory properties should also be preserved besides extending the shelf life of the said cheeses. To achieve this, appropriate preservation techniques must be employed. Storage and maturation processes can compromise the safety and quality of cheeses through various ways including microbial growth, enzymatic reactions and oxidation. The primary objective behind preservation is to inhibit degradation reactions, kill disease-causing organisms and check the activities of spoilage microorganisms [6]. In order to keep semi-hard and firm cheeses fresh, a number of methods like preservatives, temperature manipulation and packaging can be used [8]. To ensure that cheeses remain safe to eat, procedures have been put in place to maintain their flavor, texture and appearance. Moreover, sustainable preservation methods used elongate shelf life hence reduce the amount of cheese disposed along the food chain [5].

In the domain of hard and semi-hard cheeses, this article attempts to comprehend and expound the many different techniques and their corresponding technologies that are utilized to ensure their quality as well as safety. This study also looked at traditional preservation methods but focused more on current or modern ways which can be applied at the time of storage and marketing. The safety, shelf life, and sensory properties pertaining these foods vis-à-vis preservation techniques were also investigated. Moreover, it considers how environment friendly such technologies may be and their contribution towards sustainable food systems. In general, the goal is to enhance the quality and safety of hard and semi-hard cheeses by providing a comprehensive comprehension of the various approaches and their advantages and disadvantages.

2. Classification of cheese

Bovine, ewe, goat, or water buffalo milk, starter cultures, coagulant (either rennet or acid), and salt are the main components in a wide variety of cheeses, the number of which can reach approximately 1500 [9,10]. Various efforts have been attempted to categorize different types of cheese into relevant groupings or families, to aid researchers, retailers, and cheese technologists in their studies and assisting consumers in making informed choices [11]. The classification criteria encompass dairy species, coagulating agent (rennet or acid), texture/moisture content, maturity level (matured or fresh), and microbiota (internal bacterial, surface/smear bacterial, internal or surface mold, propionic acid bacterium). The classification of cheeses in traditional schemes mostly relies on their rheological qualities, which are directly linked to the moisture content. Cheeses are categorized as extremely hard, hard, semi-hard, semi-soft, or soft depending on these properties [12]. Despite being commonly used for classification, this approach has significant limitations as it combines cheeses with distinct qualities and manufacturing methods. Cheddar, Parmigiano Reggiano, Grana Padano, and Emmental are commonly classified as hard cheeses [13]. However, despite this classification, they possess distinct characteristics and are produced using distinct processes. Efforts have been undertaken to enhance the specificity of this system by incorporating variables such as the source of the cheese milk, coagulation process, coagulum cutting, curd scalding, whey drainage, salting method, and molding technique [14]. In addition in their 1972 study, Walter and Hargrove proposed a classification system for cheeses based on their manufacturing technique. They identified a total of 18 unique forms of natural cheese, which they further categorized into eight families: very hard, hard, semisoft, and soft [15]. Ottogalli, 2001 categorized cheeses into three primary categories: Lacticinia (resembling milk), Formatica (having a specific shape), and Miscellanea (many types). The Lacticinia category comprises products made from milk, cream, whey, or buttermilk through the process of coagulation using acid (lactic or citric), with or without the application of heat. A little quantity of rennet is frequently employed to enhance the solidity of the resulting coagulum, such as in the case of Quarg and cottage cheese. The Lacticinia category consists of seven families, encompassing a variety of products that range from yogurt-like items to whey-based products such as Ricotta. The Formatica category encompasses a wide range of cheese types, all of which undergo coagulation with the use of rennet. This is a diverse assortment of varieties, categorized into five classes primarily based on their moisture content: very hard, hard, semihard, semisoft, and soft. Additionally, the classification takes into account the degree and manner in which the varieties ripen, including internal ripening caused by bacteria, surface ripening caused by white mold, internal ripening caused by blue mold, and surface ripening caused by bacterial smear. The Miscellanea group comprises a diverse assortment of cheeses, including processed, smoked, grated, and pickled variations. It also encompasses cheeses that incorporate non-dairy elements such as fruit, vegetables, and spices, as well as cheese analogues and cheeses produced utilizing ultrafiltration technology [16]. McSweeney et al. (2004) and Fox et al. (2017) introduced an intricate categorization system that relies on the subsequent criteria [17].

1. Dairy animal species include cows, sheep, goats, and water buffalo.
2. Coagulant: enzymatic (rennet), isoelectric (acid), and acid-heat.
3. Texture (moisture content): extremely firm, firm, moderately firm, moderately soft, and soft.
4. Ripening agents can be categorized into four types: internal-bacterial, surface mold, internal mold, and surface bacterial smear.
5. Eyes/Openings: There are several enormous eyes, a few little eyes, and irregular openings.

Fig. 1 illustrates a variation of this approach, depicting a total of 15 groupings. This taxonomy includes examples of Italian cheeses, although it might be argued that some of the 15 classes mentioned do not contain certain Italian kinds. The categorization of Italian cheeses are made more complex by the fact that the same type of cheese can be sold after different lengths of aging (e.g., Caciotta, Pecorino cheeses), resulting in its inclusion in many groups of the classification shown in Fig. 1. Furthermore, there exists a variety of altered cheeses and cheese-like products, such as enzyme modified cheese, dehydrated cheeses, cheese mimics, and processed cheese. In Scandinavia, particularly Norway, a unique assortment of cheese-like goods is produced through the process of concentrating whey or a mixture of whey and milk, followed by the crystallization of lactose and the concentration of other particles present in the whey. One could contend that these particular types are not truly considered cheeses, but rather by-products of the cheese-making process derived from whey they bear more resemblance to fudge than to cheese [18]. The products mentioned are part of Fig. 1. These cheeses, including Brunost, Mysost, Mesost, Mysuostur, Myseost, and Braunkäse, are known for their velvety texture and a delightful taste reminiscent of caramel. Sweet whey is typically employed as the primary source, while acid whey may be utilized for some variations [19]. There are several types of this category which are made in large quantities at an industrial level such as Parmigiano Reggiano, Grana Padano (which is extra hard), Cheddar and other territorial British variations. Cheeses that contain holes inside them due to being matured by bacteria can also be classified based on their moisture content [12]. The division includes hard kinds of cheeses such as Emmental that have many large holes made when *Propionibacterium freudenreichii* subsp. *shermanii* produces carbon dioxide through fermenting lactate; there are also semi-hard kinds like Edam and Gouda where some small bubbles form as citrate gets fermented by a starter component [20].The majority of cheese kinds that are not categorized as internal bacterially-ripened cheeses are either soft or

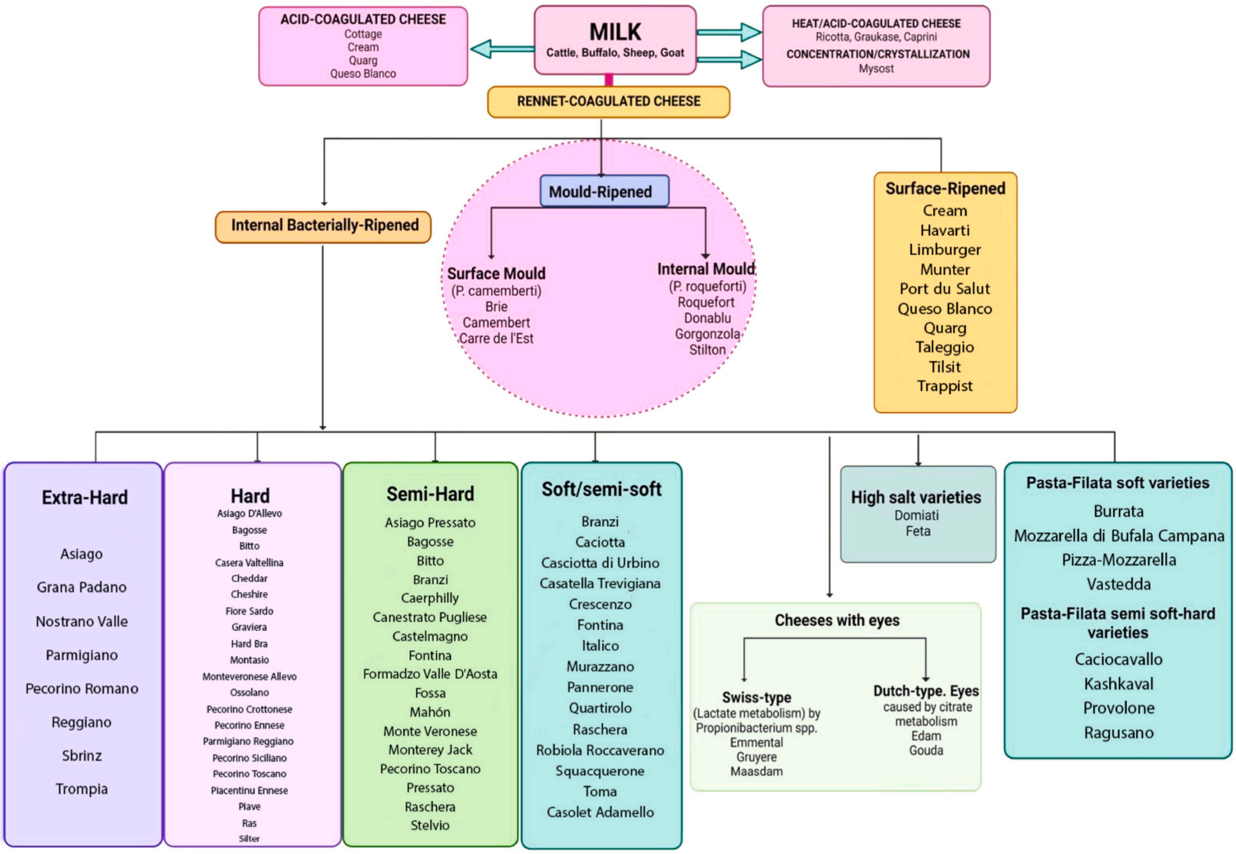

Fig. 1. The variety of cheese which classified into super-families categories based on the primary agent responsible for ripening and/or the specific production technology employed.

semi-hard. Pasta filata cheeses, such as Mozzarella and its variations, as well as Provolone, are highly significant Italian cheese types that are now manufactured and distributed globally [21]. Mold-ripened cheeses can be categorized into two types: surface mold-ripened varieties, such as Camembert or Brie, where the ripening process involves the growth of *Penicillium camemberti* on the surface; and internal mold-ripened cheeses, also known as blue cheeses, like Stilton, Danablue, Roquefort, and Gorgonzola, where *Penicillium roqueforti* grows in cracks and crevices throughout the cheese. Surface smear-ripened cheeses are distinguished by the formation of a diverse microbiota, starting with yeasts and eventually including bacteria, especially coryneforms, on the surface of the cheese as it matures [22]. Examples of such cheeses include Limburger, Munster, Trappist, and Taleggio. White, brined cheeses such as Feta and Domiati are matured in a solution of saltwater, resulting in a high salt content. Because of this, they are classified as a distinct category.

3. Types of hard and semi-hard cheeses

3.1. Definition and characteristics

Hard and semi-hard which have different features and methods of production. Hard cheeses are like Parmigiano Reggiano or Cheddar [23]. They ripen for 45 days or more with moisture content not exceeding 51 %. Also, they can be cooked at high temperatures and undergo processes such as cheddaring, milling and pressing. Mahon-Menorca or Appenzeller are examples of semi-hard cheeses that mature within 2–8 months while their moisture varies between 49% and 56 %. Curd washing might be applied to them; also cutting into small grains and then acidifying using starter cultures during the process may happen [24]. Some semi-hard varieties acquire complex microflora on their surfaces as well as being smear-ripened during maturation.

3.2. Popular varieties

Parmigiano Reggiano, Emmentaler, Gouda, Cheddar, Graviera Kritis, Idiazabal, Manchego, Raclette, and Tete de Moine are popular hard and semi-hard cheeses. The flavors, textures, and features of these cheeses are unique. Hard Parmigiano reggiano has a granular texture and a deep, nutty flavor. Swiss cheese Emmentaler has big pores and a mild, nutty flavor. Gouda is a creamy, mellow, buttery semi-hard cheese. Sharp, acidic cheddar is a popular hard cheese. Greek semi-hard cheese Graviera Kritis tastes sweet and nutty. Spanish semi-hard cheese Idiazabal tastes buttery and smokey. Spanish sheep's milk hard cheese Manchego has a deep, nutty flavor. Raclette is a creamy, flavorful Swiss semi-hard cheese that melts well. Tete de Moine, a cylindrical Swiss semi-hard cheese, tastes delicate and nutty [5,25,26].

3.3. Key factors influencing quality and safety preservation

The top factors that affect the maintenance and safety of hard and semi-hard cheese are milk quality, cheese-making techniques, conditions for ripening and Storage. The kind of milk utilized in making cheese has a great impact on its composition and microbiological features [27]. To ensure that the cheese has no faults and has the right moisture content and pH levels, all procedures used in making cheese such as curd acidification and draining must be checked carefully [28]. Protein decomposition and the creation of different tastes during cheese aging are brought about by biochemical changes. These changes are affected by how ripe the cheese is, alongside the temperature and moisture [29]. Appropriate storage methods such as keeping them in the refrigerator and using packaging that prevents oxidation and microbial growth are essential for maintaining the quality and safety of hard as well as semi-hard cheeses. Usually, the excellence and safety of hard or semi hard cheeses largely depend on the close attention paid to milk quality, accurate processing methods, suitable ripening conditions and storage practices [6,29,30].

4. Quality preservation techniques

Traditional methods have been used to store firm and semi-firm cheeses but these can destroy the quality and safety of matured products meant for wider consumption. With the increase in demand for cheese with longer shelf lives among more people who prefer eating it, technology has become the main solution when it comes to these two issues [6,31]. In fact, other techniques have been developed for preserving food items for longer periods such as high hydrostatic pressures, chemical and natural preservatives from plants, vacuum or modified atmosphere packaging, edible coatings and films among others besides these some storage and marketing technologies can be used at later stages like irradiation or light pulses [32]. Every cheese type requires a specific way of preservation and ideal conditions of usage for ensuring its quality and safety during storage. These techniques also affect on the environment and food chain sustainability [33]. Every kind of cheese requires a different way of preserving and the right kind of conditions to apply during storage to keep it good and safe for consumption. These methods have advantages and disadvantages when utilized in large scale dairy processing plants [33]. In certain places, the agriculture and food industry depends on traditional cheese making methods where raw milk is used plus its native microorganisms that give rise to the unique flavors found in hard and semi-hard cheeses [34].

5. Traditional preservation methods

5.1. Aging and maturation

Aging and maturation hold a very vital position when it comes to the preservation of hard and semi-hard cheeses through traditional methods [8]. It is necessary to carry out preservation research to expand their shelf life because these kinds of cheeses have a long life and therefore can be spoiled due to ripening [35]. To develop its distinct flavor, texture and smell cheese undergoes certain changes in microbiological, biochemical and physicochemical aspects while it matures. These changes are facilitated by starter microflora protease enzymes and milk coagulant enzymes [36]. For ripening cheese needs 15–90 days, depending on the kind Table 1 summarizes ripening times and reasons for different cheese types [18]. Optimum conditions for enzyme function are achieved by controlling the temperature and humidity levels during ripening the cheese's moisture, active acidity, and salt level are further checked throughout storage to maintain organoleptic qualities traditional methods enhancing the aging of firm and semi-firm cheeses [37].

5.2. Salting techniques

One of the oldest tricks to preserving hard or semi-hard cheese is by using salt. To extend the life of cheese, salt is utilized to inhibit the growth of bacteria that cause it to spoil and also enhances its flavor as well as texture. This is because the salinity draws out moisture while breaking down proteins into simpler compounds which gives cheeses their characteristic taste. Traditional methods for preserving hard and semi-hard cheeses include salting. Different salting methods alter cheese's physio-chemical, sensory, and volatile constituents during ripening [42,43]. Salting is done during curd processing in conventional hard and semi-hard cheese manufacture. The cheese is brined or rubbed with dried salt. Cheese absorbs salt based on brine concentration, curd wetness, and surface area. Salting reduces moisture, promotes helpful bacteria, and inhibits bad bacteria [44]. Salting helps generate the appropriate flavor profile and extends cheese shelf life [26]. Cheese flavor and quality depend on processing technologies and microbial community structure during manufacture and ripening [45]. Sodium chloride affects taste, aroma, texture, pH, water activity, and microbiological development in cheese manufacture and ripening, making salt reduction difficult. Any salting method alteration may disrupt this delicate equilibrium, affecting cheese quality [46].

6. Impact of preservation techniques on flavor and texture

The flavor and texture of hard and semi-hard cheeses are affected by preservation techniques. Low temperature freezing can maintain the sensory attributes of the cheese; however, it is essential to use packaging materials that will prevent the cheese from freezing injuries [47]. To improve the shelf life of cheese, its sensory and quality attributes could be retained by using high hydrostatic pressure (HHP) processing during storage [48]. While excessive CO_2 can influence taste compounds, MAP using gas blends like CO_2 and N_2 will hinder bacteria development and maintain cheese quality [49]. Vacuum packaging may also be implemented to preserve cheeses; however, it may induce modifications in flavor and texture [50]. In general, the best way to decide how to store food for future use is to think about three things: how long you want it to last before you eat it; what it should smell, taste, or look like when you do eat [51].

7. Microbial safety

7.1. Starter cultures

7.1.1. Bacterial starter cultures

Since fermented foods were traditionally made using diverse bacteria, yeasts, and molds, current starter cultures should include them. Most cheese, cultured dairy, fermented sausages, and fermented veggies were made using bacteria. Yeasts are employed in the production of bread and alcoholic beverages, while molds are utilized in the creation of cheeses, sausages, soy sauce, and tempeh [52]. The organisms present in a starter culture preparation are typically clearly identified, often down to the species or even strain level, and are meticulously chosen based on specific criteria that are important for a particular product. Certain starter culture organisms, on the other hand, lack a precise definition and are instead chosen based on a track record of proven effectiveness. However *lactic acid bacteria* (LAB) are unequivocally the most crucial category of bacteria employed as starter organisms [53]. The LAB is comprised of a group of

Table 1
Ripening times and reasons for different cheese types.

Cheese type	Ripening time	Reason	Ref.
Fresh cheese	0–15 days	No ripening needed; consumed fresh for mild flavor.	[38]
Soft cheeses (e.g., Brie)	15–30 days	Mold ripens surface for creamy texture, mild flavor.	[38]
Semi-hard cheeses (e.g., Gouda)	30–60 days	Protein and fat breakdown for nutty flavors, firmer texture.	[39]
Hard cheeses (e.g., Cheddar)	60-90+ days	Long ripening reduces moisture, enhances sharp flavor.	[40]
Blue cheeses (e.g., Roquefort)	60-90+ days	Mold growth for tangy flavor and creamy texture.	[41]

low gram-negative and gram-positive cocci and rods belonging to at least 11 different genera [54]. However, only a small number of these genera are utilized as starter cultures, as indicated in Table 2. Lactococcus lactis subsp. lactis has traditionally been regarded as the predominant *lactic acid bacteria* (LAB) in cheese production [55]. However, other species, notably *Streptococcus thermophilus*, have also become significant due to their utilization in yogurt and mozzarella cheese production (Fig. 2). Generally, LAB are heterotrophs that lack catalase activity and have intricate nutritional needs. Their metabolism is fermentative, meaning they obtain energy through substrate-level phosphorylation, resulting in the production of adenosine triphosphate (ATP). There are two types of sugar metabolism: homofermentative and heterofermentative [56]. Homofermentation involves the direct conversion of over 90 % of the sugar substrate in starter cultures into lactic acid. On the other hand, heterofermentation results in the production of lactic acid, acetic acid, CO_2, and ethanol [57]. While the majority of genera are exclusively one or the other, certain species of *Lactobacillus* possess the biochemical capability to engage in both pathways. Both hetero- and homofermentative lactic acid bacteria (LAB) are employed as starter cultures [58]. Their optimal temperature for growth varies; however, the majority of LAB used as dairy starter cultures are either mesophilic (*Lactococcus lactis*) or moderate thermophiles (*S. thermophilus and Lactobacillus* spp). The primary role of starter culture bacteria is to undergo fermentation of sugars and generate acids [59]. Therefore, the capacity of lactic acid bacteria (LAB) to metabolize carbohydrates is of utmost significance the selection of strains can be based on the specific range of substrates they can metabolize and the rate at which metabolism occurs [60]. In dairy fermentations, rapid lactose fermentation is necessary, while in sourdough fermentation, the metabolism of maltose and glucose is significant, and in sausage fermentation, the metabolism of glucose or sucrose is of utmost importance. Furthermore, these bacteria are frequently chosen based on their proficiency in carrying out additional metabolic functions. The enzymatic breakdown of proteins through proteolytic and peptidolytic enzymes is crucial for the development of the desired flavor and texture in aged cheese [61]. The starter culture bacteria used in the production of sour cream and cultured buttermilk must have the capacity to metabolize citrate and produce the aromatic compound diacetyl. The production of exopolysaccharides by *S. thermophilus* strains is advantageous in yogurt as it enhances its viscosity [62]. The conversion of malic acid to lactic acid by malolactic bacteria is an essential process in wine-making, as it helps to decrease the acidity of specific grape varieties [63]. While LAB are undeniably the predominant and crucial group of bacteria employed as starter cultures in fermented foods, additional bacteria are also utilized (Table 2). *Propionibacterium shermanii* and *Brevibacterium* linens are employed in the production of Swiss (and similar types) and Limburger, Muenster, and Brick cheeses, respectively, within the cheese industry [64]. These bacteria are utilized as starter cultures during the cheese-making process. For more information, refer to the sections on types of cheese, chemistry of gel formation, chemistry and microbiology of maturation, manufacture of extra hard cheeses, manufacture of hard and semi-hard varieties of cheese, and cheeses with 'eyes' [65]. Types of cheese include soft and special varieties, white brined varieties, quarg and fromage frais, and processed cheese. Cheese also has dietary importance. Mold-ripened cheeses include Stilton and similar varieties, as well as surface mold-ripened cheese varieties [66].

7.1.2. Mold starter cultures

Mold cultures are employed in the production of various types of cheeses, such as all variations of blue cheese, as well as the white surface mold-ripened cheeses exemplified by Brie and Camembert (Table 3). Blue mold cheeses are produced by utilizing spore suspensions of *Penicillium roqueforti*, while white mold cheeses are created using *P. camemberti* [67].

7.2. Role of starter cultures to improve the safety and quality cheese

Starter cultures play a vital role in cheese production, as they have a profound impact on the development of flavor and texture, as well as ensuring microbial safety. Starter cultures consist of meticulously chosen strains of bacteria, typically lactic acid bacteria (LAB) like *Lactococcus*, *Streptococcus*, and *Lactobacillus* [69]. These cultures are introduced into milk to commence the fermentation process. Given the significant role of the starter in cheese production and maturation, it is logical to assume that variations in the enzyme composition of starter strains have an impact on the quality of the cheese [70]. When choosing traditional appropriate indigenous starter cultures for cheese making, various technological properties and metabolic activities such as acidification, proteolysis, lipolysis, diacetyl-acetoin production, citrate utilization, and CO_2 production [71]are assessed (Fig. 3).

Table 2
Starter cultures consist of lactic acid bacteria [68].

subspecies	Application
Lactococcus lactis subsp. *lactis*	Cheese and cultured dairy items
Lactococcus lactis subsp. *cremoris*	
Lactococcus lactis subsp. *lactis biovar. diacetylous*	
Lactobacillus helveticus	
Lactobacillus casei	
Leuconsotoc lactis	
Leuconsotoc mesenteroided	
Lactobacillus delbrueckii subsp. *bulgaricus*	Cheese, yogurt
Streptococcus thermophilus	
Brevibacterium linens	Cheese: pigment, surface
Propionibacterium freudenreichii subsp. *shermanii*	Cheese: eyes in Swiss
Penicillium camemberti	Cheese: surface ripens white
Penicillium roqueforti	Cheese: blue veins, protease, lipase

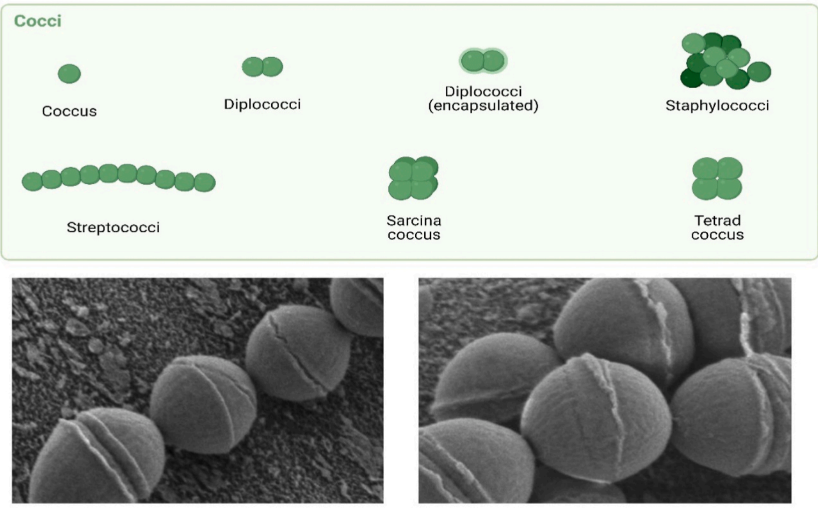

Fig. 2. Transmission electron microscopy (TEM) image *Streptococcus thermophilus.*

Table 3
Preserving the distinctive sensory characteristics of traditional cheeses and prevents standardization caused by commercial starters.

Type Strain	Applied cheese	Cheese's impact	Ref.
L. lactis BGAL1–4, L. brevis BGGO7–28, and *L. plantarum* BGGO7-29	White pickled cheese	Comparable sensory characteristics	[99]
Limosilactobacillus fermentum CRL1799 and CRL1803, *Lacticaseibacillus rhamnosus* CRL1808, and *Enterococcus faecium* CRL1785	Goat milk cheese that is spreadable	The addition of the CRL1808 strain, known for producing exopolysaccharides, to the inoculum mixture enhanced the sensory analysis.	[100]
Lactococcus lactis subsp cremoris KM746 and *Lactococcus lactis* subsp lactis KM721	Karish cheese	No change in chemical composition or physicochemical properties; Enhance the texture. Conservation of distinctive sensory attributes	[101]
Lactiplantibacillus plantarum NA18 and *Lactococcus lactis* FT27, N16, and SV77	Gorgonzola cheese	Restricted the proliferation of *Listeria monocytogenes*	[81]
Levilactobacillus brevis 2–392, *Lactiplantibacillus plantarum* 1–399, and *Enterococcus faecalis* 1–37, 2–49, 2–388, and 1–400	Canastra cheese		[102]
Streptococcus macedonicus 62GT0 and *Lactococcus lactis* LC51	Giuncata and Caciotta Leccese cheeses	Positive impact on the sensory characteristics of both cheeses	[103]
Lactiplantibacillus plantarum 1QB77	Microcheese made from cow's milk	Restricted the proliferation of *Staphylococcus aureus* and *Listeria monocytogenes.*	[104]
Lactococcus lactis ESI 515 *Lactococcus lactis* CL1 *Lactococcus lactis* CL2 *Lactococcuslactis,* 623	Ripened cheese	Producers of nisin and pediocin	[105]

Preserves traditional cheeses' sensory qualities and prevents commercial starters from standardizing them (Table 3). Lactic acid bacteria (LAB) are the main microbial cultures used to ferment cheese and yogurt [72]. Protein degradation during cheese aging affects flavor, texture, and appearance [73]. Rennet, plasmin, starting proteinases, peptidases, and lactobacilli enzymes aid proteolysis. Proteolysis hydrolyzes proteins into peptides and free amino acids (FAA). These FAA molecules are precursors of flavor-forming processes [73]. Lactobacilli, a specific strain of non-starter lactic acid bacteria (NSLAB), were incorporated into milk during the cheese production process in a study conducted by Rehman et al. The researchers noted that the cheese that resulted had a more pronounced flavor due to the elevated levels of free amino acids (FAA) [74]. Additionally, some studies are specifically focused on the evaluation of the flavor impact of a variety of non-starter lactic acid bacteria (NSLAB) strains. Awad et al., 2007 investigated the sensorial characteristics of Ras cheese produced using NSLAB alone and a combination of NSLAB and SLAB in their investigation. The NSALB cheese having more than 1 non-starter lactic acid bacteria (with *Lactobacillus paracasei* subsp. *paracasei, Lactobacillus delbrueckii* subsp. *lactis, and Enterococcus faecium*), which was specifically produced with *Lactobacillus helveticus*, received the top scores for overall acceptability, texture, and flavor [75]. The detection of non-starter lactic acid bacteria by high-throughput sequencing has been the subject of several studies. Biolcati et al. used High-Throughput Sequencing (HTS) to study the changes in microbial populations during the production of an artisanal cheese. Non-starter lactic acid bacteria (NSLAB) such as *Leuconostoc mesenteroides*, *Lactobacillus helveticus*, *Lactobacillus zeae*, and *Enterococcus* spp. appeared in low numbers after ripening [76]. NSLAB (non-starter lactic acid bacteria) are what fermented the remaining lactose or other forms of carbohydrates. They also produced amino acids, peptides, citrate, and aromatic compounds while helping in ripening the cheese further [76]. The research carried out by Aldrete-Tapia et al., 2014 observed the

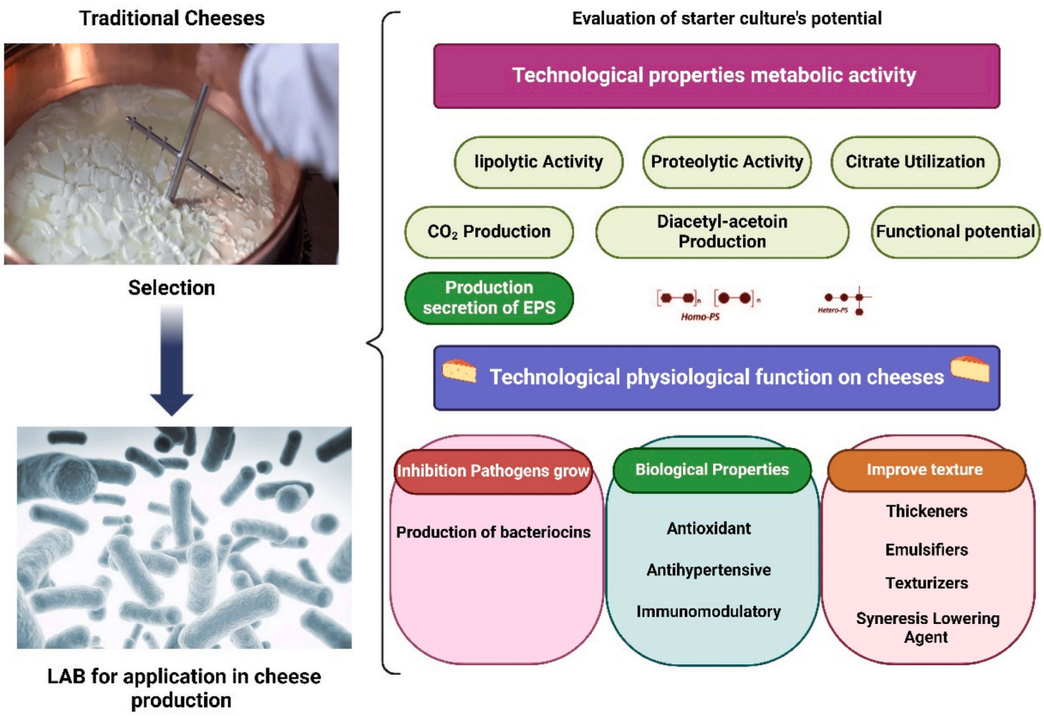

Fig. 3. Utilization of indigenous cheese microorganisms for cheese manufacturing.

existence of *L. plantarum* in old milk having positive influence on sensory qualities. No deliberate contamination of milk with strains of lactic acid that do not serve as supplementary cultures or form part of the primary starter culture has been done [77]. Raw milk is a prominent source of NSLAB, as stated by Montel et al. (2014). The NSLAB has also been extracted from different areas within cheese production facilities, such as floors, drains, and equipment surfaces [78]. According to Choiet al. (2020) cross contamination can contribute to the presence of non-starter lactic acid bacteria (NSLAB) in cheese [79]. They found that some NSLAB in their cheese samples were likewise in the starter lactic acid bacteria (SLAB) of other cheeses made in the same facility. Most belong to *Lactococcus, Lactobacillus, Leuconostoc, and Pediococcus*. Apart from LAB, Propionibacterium and Bifidobacterium are also used. Moreover, the main foodborne pathogens associated with cheese outbreaks are enteropathogenic *E. coli*, specifically the strain 0157:H7, *Salmonella* spp*., S. aureus, and L. monocytogenes* [80]. Nevertheless, it is crucial to thoroughly evaluate the management of surface contamination caused by *L. monocytogenes* by LAB during the ripening or storage process. This is because the vulnerability of *Listeria* spp. to the antimicrobial effects of LAB varies depending on the strain [81]. Other authors have reported the susceptibility of this strain, as evidenced by the addition of starter *Lactococcus lactis* in fresh cheese resulting in a slight reduction in *L. monocytogenes* counts [82]. The inclusion of tartaric, fumaric, lactic, or malic acid enhances the suppression of *L. monocytogenes* [83]. The synergistic interaction of organic acids with lactic or acetic acid, which LAB naturally produces during cheese maturing, affects their potency.*Staphylococcus aureus* is a common problem in making cheese since it produces toxins that cannot be easily destroyed during cooking thus a need for control. These toxins remain the major cause of staphylococcal food poisoning following contamination at any stage. *S. aureus* is abundant in milk, so controlling its contamination is critical in raw milk cheeses [84]. Microbiological standards for *S. aureus* in cheese have been established by legislation [85]. However, some studies suggest that its growth is prevented in raw milk during ripening [86]. For example, it has been shown that *S. aureus* can survive in commercially produced starter white cheese up to 60 days. It was observed that addition of *L. rhamnosus* and *Lactobacilluscasei Shirota* probiotics inhibited up to 5 Log cfu/g. Perhaps this can be explained by the fact that there is an increase in bacteriocin production with maturing process [87]. Yet, asic *L. rhamnosus* failed to bring down *S. aureus* in minas frescal cheese from Brazil [88]. *S. aureus* was seen in Jben fresh cheese from Morocco [89]. On the other hand, the addition of nisin-producing bacterium *Lactococcus lactis* subsp. lactis UL730 (4 days) for this reason the safety increased during the shelf-life of fresh cheese. In their investigation, *Lactobacillus lactis* subsp. Utilizing high-pressure treatment (HPT) at reduced pressure, in conjunction with lactic acid bacteria (LAB) that produce bacteriocin, enhances the safety of raw cheese against *S. aureus* [90]. The disruption of the structure of *S. aureus*, particularly its cell membrane, by HPT may account for the increased efficacy of bacteriocins produced by starter LAB. During the ripening and storage periods in cheese processing, the presence of Salmonella spp. decreases [91]. The primary obstacles that hinder its growth are factors such as salt concentration, storage temperature, and pH. Often, *Salmonella* spp. can persist until the final product. In addition, laboratory scale preparation of soft cheese artificially contaminated with low levels of *Escherichia coli O157*, *Listeria monocytogenes*, and *Salmonella enterica Serovars Typhimurium*, *Enteritidis* [92]. Therefore, it has been proposed that the decrease in *S. typhimurium* during the ripening process of Montasio cheese is linked to the decline in pH following the inhibitory effect of the starter bacteria *Lactobacillus plantarum*, as observed through the spot method [93]. On the other hand, fast acidification is brought about by lactic acid bacteria, which are natural to LAB, and starter cultures, while it may be slowed down by *E. coli*. *E. coli* can survive longer in the course of maturation may be attributed to the indigenous bacteria in raw milk [94]. The use of Zataria multiflora EO in combination with *Lb. acidophilus* starter cultures have been researched on for their ability to hinder the growth of *E.coli*. When tested in this experiment it was noted that these two compounds acted synergistically resulting in lowering the growth rate of *E.coli* (Mehdizadeh et al., 2018) [95]. complete growth inhibition was achieved when lactic acid bacteria LA-5 was mixed with oregano plus rosemary essential oils [96]. The combination of bacteriocinogenic starter cultures and high pressure which is hydrostatic led to decrease levels of *E. coli* at ripened cheese even under low pressure level [97]. Studies have shown that Lb. reuteri or glycerol during semi-hard cheese production does not inhibit *E. coli* O157:H7 growth for up to 30 days Nevertheless, the combination of Lb. reuteri and glycerol effectively eradicates *E. coli* within 24 h [98]. As shown in Fig. 4, various lactic acid bacteria (LAB) cultures utilized for fermenting milk in dairy products.

7.3. Growth of pathogens in cheese during ripening hard and semi hard cheese

The fate of various pathogens in Emmental and Cheddar cheese is monitored throughout the maturation process. Both Emmental and Cheddar are types of hard cheeses with nearly identical pH values of approximately 5.2 immediately after production. The specific metabolic activity of ripening bacteria was quantified by real-time reverse transcription PCR throughout Emmental cheese production. Except for of small amounts of *S. aureus*, no other disease-causing microorganisms were detected in Emmental cheese within 24 h of production. This is because the cheese is made using a high cooking temperature of approximately 53 °C. The populations of *S. aureus*, *E. faecalis*, *E. coli*, and *Salmonella* spp. all decreased during the ripening process of cheddar cheese at a temperature of 12 °C [106]. Additionally, the Gram-negative bacteria exhibited a more rapid decrease in population compared to the Gram-positive organisms [107]. An issue with *S. aureus* is that although the organism's population decreases significantly during ripening, there may have been high numbers of it during the initial stages of ripening [108]. These high numbers can result in the production of enough enterotoxin to cause food poisoning. The enterotoxins exhibit considerable stability throughout the process of cheese ripening and are not significantly broken down by the chymosin or bacterial proteinases found in the cheese during ripening [109]. Consequently, the enterotoxins may still be present in the cheese when it is consumed. Hence, it is plausible that cheese with a low concentration of *S. aureus* could harbor a substantial amount of enterotoxin then population of *L. monocytogenes* in cheddar cheese also diminishes during the maturation process at a temperature of 6 °C, although there is some variability observed in different experimental trials Ryser and Marth [110]. However, there is a substantial mortality rate. There was also a slight variation in the rate of decline of *L. monocytogenes* in cheese ripened at 13 °C, although the differences were generally insignificant. In a recent study by Dalmasso and Jordan (2014), it was discovered that *L. monocytogenes* did not exhibit growth in raw milk Cheddar cheese that was naturally contaminated [111]. The contamination levels were extremely low, requiring enrichment to detect them. However, analysis revealed the presence of 11 distinct PFGE patterns among the isolates. One of these patterns was found in samples taken from the farmyard, the processing area floor, and the cheese, suggesting a potential pathway of contamination. Schlesser et al. (2006) conducted a comprehensive study on the viability of a 5-strain mixture of *E. coli* 0157:H7 in raw milk Cheddar cheese that was aged at a temperature of 7 °C for a duration of 1 year. Three distinct levels of organisms were employed, namely, 10 5, 10 3, and 10 cfu/ml of raw milk [112]. Three trials were conducted at each level. The findings indicated a gradual decline in the figures across the three varying concentrations of the mixture. Moreover, the

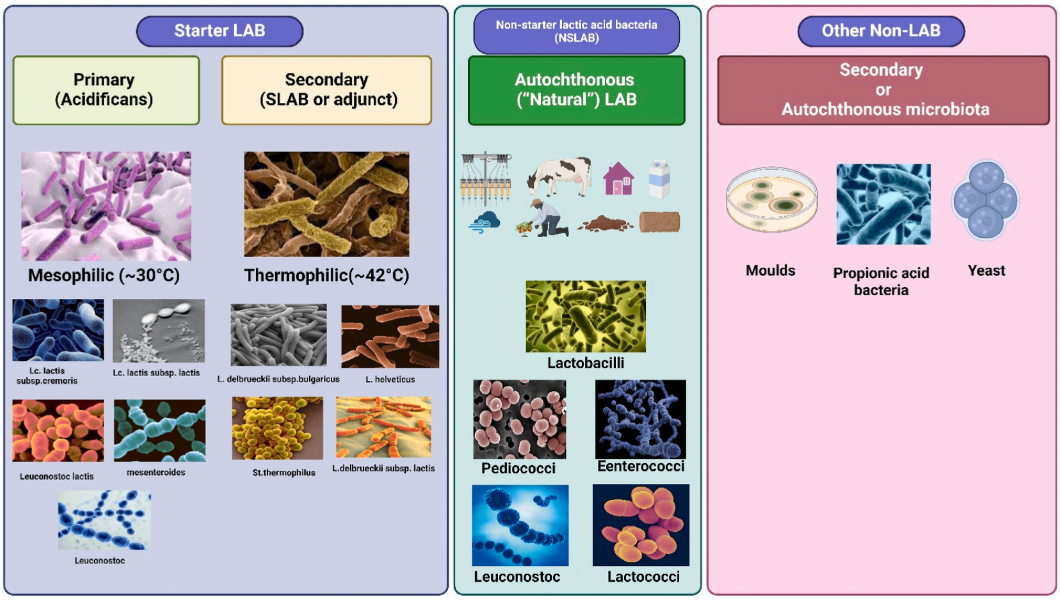

Fig. 4. Various strains of lactic acid bacteria (LAB) are employed in fermenting milk to produce dairy products.

existing US guideline, which mandates that raw milk hard cheese must be aged at a temperature exceeding 1.7 °C for a duration of 60 days before its release into the market, is inadequate in guaranteeing the absence of harmful microorganisms in the cheese. The data for the intermediate level exhibited variability initially, leading to an impact on the slope and regression coefficient. However, the slopes for the high and low levels were essentially identical, indicating that the rate of decrease remains constant irrespective of the initial level of the cells utilized. Peng et al. (2013) discovered comparable outcomes regarding the viability of five non-O157 strains of *E. coli*, including three strains that produce Shiga toxin, in a semi-hard cheese that was matured at a temperature of 13–14.5 °C for a duration of 16 weeks [113]. The observed increase of approximately 3.5 logarithmic units in the population of *E. coli* on day 1 was attributed to the combined effects of growth and concentration. Subsequently, there was a gradual and uninterrupted decline in all strains throughout the 16-week maturation period. The rate of decline of *E. coli* in the cheddar cheese is 4.5 times faster. The reasons for this are ambiguous [114]. In the United States, cheeses produced using unpasteurized milk must be aged for at least 60 days at a temperature of 1.7 °C. If this requirement is not met, the milk used for making the cheese must undergo the process of pasteurization [115]. The findings mentioned above indicate the necessity to reconsider this regulation. In the study this characteristic was also for it was the ability to survive in Tilsit cheese during the ripening process of Tilsit cheese at a temperature of 12 °C for 30 days, the numbers of all tested pathogens, except for *L. monocytogenes*, decreased. The decrease remained fairly constant for *L. monocytogenes* [116]. After the initial 30 days, there was a gradual decrease of approximately 1 log cycle over the next 2 months. The stability of *L. monocytogenes* in this cheese was ascribed to the comparatively low cooking temperature and brief cooking duration (42 °C for 15 min), which exhibited bacteriostatic rather than bactericidal properties. The pH and temperature during ripening are also significant factors. The pH level rose from 5.2 on day 1–5.8 on day 90 [117]. Typically, commercially available samples have a pH level of approximately 6.2 after 90 days of ripening. *L. monocytogenes* exhibits a broad temperature tolerance, thriving in temperatures ranging from −1 to 45 °C [118]. The acidity level of the cheese was also crucial *Salmonella* exhibited rapid mortality at pH levels of 5.03 and 5.23, but showed no mortality at pH 5.7. A pH level of 5.23 within 24 h of production is commonly observed in high-quality Cheddar cheese, whereas a pH level of 5.7 may suggest inadequate starter activity, possibly due to the presence of phage contamination, antibiotic residues in the milk, or a combination of both factors [119].

7.4. Control of undesirable microorganisms

Hard and semi-hard cheeses are vulnerable to spoilage by diverse microorganisms throughout their aging and storage phases. In order to avoid decay, a range of preservation methods are utilized, such as high-pressure processing, the application of antifungal additives, and the regulation of microbial proliferation by employing elevated levels of CO_2. Rod-shaped bacteria exhibit greater sensitivity compared to cocci, while endospores demonstrate exceptional resistance to high-pressure processing treatments [120]. Antifungal additives, such as sorbates, benzoates (Fente-Sampayo et al., 1995), and natamycin [121], are commonly employed in cheese production to prevent fungal contamination. The microbiota of cheese can be categorized into two groups: primary starter cultures, consisting of lactic acid bacteria (LAB) that initiate fermentation, and secondary microbiota, which encompasses non-starter lactic acid bacteria (LAB), yeasts, and molds [122]. Stringent control over anaerobic microorganisms is essential to prevent spoiling the taste of cheese by giving out compounds that affect it negatively. Microbial lipases and proteases when available can lead to formation of unwanted flavors and smells thus affecting quality of cheese generally. The presence of anaerobic microorganisms is checked strictly in order to stop them from producing volatile compounds that could affect the taste of cheese [123] Below, methods to control undesirable microorganisms are discussed.

7.4.1. High-pressure processing (HHP)

For hard and semi-hard cheeses, high-pressure processing, or HPP, is a technique used to manage unwanted microbes. HHP treatments can reduce spoilage microorganisms and eliminate pathogens without affecting the lactic bacteria responsible for the final characteristics of the cheese [124]. However, rod-shaped bacteria are more sensitive than cocci, and endospores are highly resistant to HHP treatments, particularly *Clostridium* spp. In the case of a 600 MPa treatment applied to cheese at 30 and 50 ripening days, no sensory and proteolytic changes were observed, whereas spoilage microorganisms experienced a greater reduction [125]. Inácio et al. (2014) reported a significant reduction in the microbial count of Enterobacteriaceae, Listeria innocua, molds, and yeasts in raw milk ewe's cheeses treated with high pressure. HHP treatments can be used to control microbial growth and prevent spoilage during cheese production [126]. During HHP treatment, the product is subjected for a short time (10–20 min) to a very high pressure level (400–600 MPa is normally used at the industrial scale) and a temperature below 45 °C. Based on the isostatic principle, pressure applied in HHP treatments is transmitted instantaneously and uniformly throughout food, regardless of size, shape, and composition [127]. It has been documented that pressures exceeding 500 MPa result in a decrease in proteolysis, which prevents the excessive ripening of fresh, soft, and semi-hard cheeses ([128,129]. Additionally, it slows down chemical and enzymatic reactions that occur during refrigerated storage, both at retail locations and at home. HHP can inhibit the growth of microorganisms during storage. On the other hand treatment of 200 MPa for 20 min was applied either to starters (*Streptococcus thermophylus, L. lactis, and Lactobacillus bulgaricus*) or to ripened sheep cheese at the beginning of ripening, and cheese characteristics were compared with those of untreated control cheeses [130]. All cheese samples were stored for 90 days at 4 °C. Kinds of cheese from HHP-treated starters presented the higher sensory scores, and no bitterness was detected during storage. Secondary proteolysis was higher in these cheeses than in the other cheese samples, whereas the HHP-treated cheeses showed the highest aminopeptidase activity [131]. Furthermore, HPP treatment has demonstrated efficacy in eradicating pathogens present in cheese. Such is the case with *Escherichia coli* tested in model semi-hard cheeses [132]. and used HPP treatment for or Listeria spp [133]. In Ibores cheese, however, high pressure processing (HPP) treatments are highly effective in controlling microbial-related flaws in cheese. HPP (High-Pressure Processing) can effectively control the growth of coliform bacteria within a pressure range of 200–400 MPa [124]. Additionally, moderate pressure levels of 300–500 MPa can be utilized to manage the spores of *Clostridium tyrobutyricum* [134]. A pressure of 500 MPa significantly impeded the growth and spread of diverse microorganisms, such as total aerobic mesophiles, thermophilic starters, and non-starter bacteria (NSLAB) [135]. High pressure treatment of raw milk ewe's cheeses resulted in a notable decrease in the number of *Enterobacteriaceae*, *Listeria innocua*, molds, and yeasts present in the cheese [135]. The application of high hydrostatic pressure (HHP) treatment at a range of 400–600 MPa to cheese after 45 days of ripening did not result in significant changes to its physico-chemical properties. However, it did lead to a reduction in lipid oxidation compared to cheeses that were not subjected to pressure, after 100 days of ripening. Exposing Cheddar cheese slurries to treatments of 400 MPa for 20 min, while inoculated with microorganisms, resulted in a reduction of 3 log units [136]. For *staphylococci* was more pronounced in ewe's cheeses treated with 400 MPa compared to the other cheeses [136]. The aforementioned results demonstrate the utilization of HHP treatments on various dairy products, including starters, milk, curds, and hard and semi-hard cheeses, at different stages of ripening [137]. High hydrostatic pressure (HHP) treatment within the range of 200–400 MPa can serve as a dependable method for diminishing or eradicating cheese pathogens and undesirable microorganisms that contribute to defects in cheeses [138]. Table 4 provides a concise overview of the dosage of HPP with the effects on the cheeses, while Fig. 5 shows the effects of HPP on microorganism species and duration and dose used some advantages and disadvantages.

7.4.2. Antifungal additives

Cheeses frequently experience fungal spoilage, resulting in substantial financial losses for the dairy sector. Antifungals are used as surface treatments; however, there may be issues regarding the contamination of cheese with toxins and the resulting health risks. On the other hand, we have antifungal additives, like natamycin, which are frequently employed to inhibit fungal contamination in the manufacturing and preservation of hard and semi-hard cheeses. Natamycin has demonstrated efficacy as an antifungal preservative in a range of food items, such as cheeses, yoghurt, sausages, and juices ([146]. Research has demonstrated that the safety of Mozzarella cheese can be improved by suppressing the proliferation of undesirable microorganisms through the incorporation of natamycin into hydroxyethylcellulose films [147]. Furthermore, natamycin when used in food wrapping films helps maintain the quality of soft cheese by controlling molds and yeasts that may be present in it [146]. Therefore, antifungals like natamycin are essential for preventing fungal contamination and preserving hard and semi-hard cheeses [116]. Cheese is usually preserved using an antifungal called natamycin. This is produced by the bacteria *Streptomyces natalensis* and *S. chattanoogensis*, which prevents the growth of small fungi. During ripening, natamycin is applied in cheese production to stop molds that could spoil or worsen it. The use of natamycin is controlled by the EU and is also compliant with food regulations. If appropriately used, it prevents deterioration throughout manufacture and storage [148]. This preservative exhibits strong efficacy in inhibiting the growth of mold and yeast, but it does not possess the same effectiveness against bacteria. It is typically used in concentrations ranging from 1 to 20 parts per million [149]. Yangilar et al. (2017) evaluated the effectiveness of natamycin in inhibiting mold growth in Kashar cheese after 60 and 90 days of ripening, using a 0.07 % (w/w) concentration of the additive [150]. There were no discernible sensory distinctions between the cheeses with and without natamycin. Natamycin is a favorable choice because it has a high level of effectiveness when compared to other fungicides like potassium sorbate or propionic acid. Additionally, it has very minimal migration from the surface to the interior of the cheese matrix [151]. Finally, we have some natural source used for antifungal activity. The antifungal activity of eight essential oils including cinnamon leaf or bark, basil, ginger, lemon, peppermint, pine needle, and spearmint, was evaluated in vitro. The results showed that

Table 4
The effect of HPP (High Pressure Processing) on the cheeses.

HHP treatments	Time	Type cheeses	Effects	Ref.
200–500 MPa	10 min	raw ewe milk cheeses	- hindered the creation of certain volatile compounds. - Synthesis of unbound amino acids	[139]
400 MPa	5–10 min	Reggianito Argentino cheese	- Cheeses treated at 400 MPa had higher nitrogen content, soluble peptides, and free AA production. - Increased proteolysis rate accelerated ripening.	[140]
400–600 MPa	5 min	Brie cheese	- higher flavor quality than control cheese after 60 days. - Control cheese had the least residual casein during refrigeration, while 600 MPa cheeses had the most. From 21 to 60, hydrophobic peptides increased 7.6-fold in control cheese and 0.8–1.6-fold in HP-treated cheeses.	[141]
300–400 MPa	10 min	Serena cheeses	- The aroma quality and intensity scores were lower than control cheese of the same age.	[142]
600 MPa	3 min	cheddar cheese	-HPP greatly reduced the LTmax values of natural and processed cheeses. - Cheeses had more intact casein than industry samples. -HPP reduced residual rennet activity and intact casein degradation in cheddar cheese.	[143]
50–600 MPa	5–10 min	Turkish white cheese	-The greatest *L. monocytogenes* reduction. -Inhibits total molds, yeasts, and *Enterobacteriaceae*	[144]
200–500 MPa	10 min	semi-hard cheeses	-Compared to cheeses without spores, 200 MPa cheeses had LBD, reduced lactic, citric, and acetic acids, increased pyruvic, propionic, and butyric acids, 1-butanol, ethyl and methyl butanoate, and ethyl pentanoate. -Cheeses with clostridial spores and HP-treated at ≥ 300 MPa did not show LBD symptoms and had comparable organic acid and volatile compound profiles to HP-treated control cheeses, despite low spore reduction Fewer C. tyrobutyricum spores	[145]

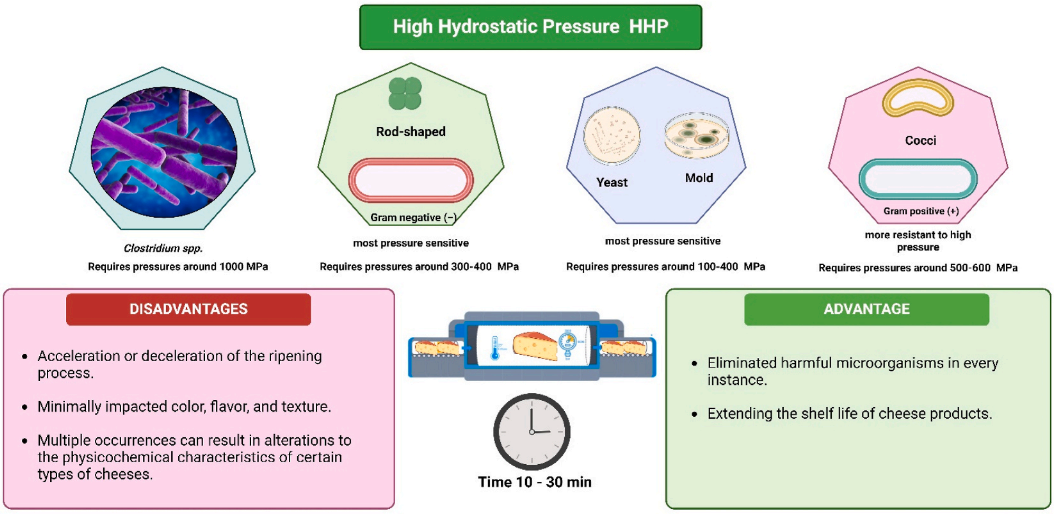

Fig. 5. Impact of high hydrostatic pressure (HHP) on different species of microorganisms, along with the effects of varying duration and dosage, as well as the advantages and disadvantages.

cinnamon leaf and bark had the highest antifungal activity [152]. The primary constituents of both cinnamon essential oils were eugenol, cinnamaldehyde, and linalool. Hence, (10–20 μL) of cinnamon leaf and bark essential oils were applied on the surface to assess their antifungal properties during the ripening process of Appenzeller cheese. The cheese exhibited antifungal properties when infused with cinnamon essential oils at an ideal concentration of 10 % v/v, without impeding the growth of the starter culture. Oregano is another viable option for a natural preservative [153].

7.4.3. Antibacterial additives

Antibacterial additives are used in hard and semi-hard cheeses to prevent the growth of undesirable microorganisms and ensure food safety. These additives can be added during ripening and storage as antifungal and antibacterial agents to avoid problems in ripened cheeses [154]. Some of the regulated additives approved for use in ripened cheeses include lisozyme, sorbic acid/sorbates, nisin, hexamethylene tetramine (HTM), nitrates/nitrites, and propionic acid/propionates, used natural based Essential oil and herbs. These additives play a crucial role in ensuring the safety and quality of hard and semi-hard cheeses by controlling the growth of undesirable microorganisms, however, Lysozyme is a naturally occurring enzyme that is found in large quantities in egg whites and is commonly extracted for industrial purposes. Due to its natural origin, this enzyme has garnered significant attention as a preservative in the food industry [155]. It exhibits bactericidal properties against Gram-positive bacteria, including LAB and clostridia, and to a lesser degree against Gram-negative bacteria. Therefore, its utilization in industry is restricted and This enzyme has been employed to mitigate the occurrence of the "late blowing" defect in hard and semi-hard cheeses due to its efficacy in breaking down the vegetative cells of *C. tyrobutyricum* and *C. perfringens*. Additionally, it is the preferred choice for reducing the concentration of nitrosamines in food [156,157]. The concentration of lysozyme in cheese varies, with reported levels between 30.8 and 386.2 mg/kg in commercial cheese samples. An important issue with the use of lysozyme is its allergenic activity. Sorbic acid and its salts, such as potassium sorbate, serve as antimicrobial additives in hard and semi-hard cheeses to inhibit the proliferation of undesirable microorganisms, specifically yeasts and molds [158]. Sorbic acid is a naturally occurring compound that is frequently produced artificially for its application as an antimicrobial preservative in food items. The minimum inhibitory concentration of sorbate required to prevent microbial growth on the surface of cheese is approximately 300 mg/kg [159]. However, this threshold may differ depending on the taxonomic classification of the spoilage microorganisms present in each specific cheese variety. Because these chemicals are quickly metabolized by metabolic pathways that lipid acids also used, they are safe food additives, meaning they have little to no poison [160]. Sorbic acid and its salts are necessary for ensuring the safety and quality of hard and semi-hard cheese. This is achieved by checking unwanted microorganisms. The growth of other organisms is limited in hard and semi-hard cheeses by bacteriocins which are antimicrobial peptides that are manufactured by lactic acid bacteria (LAB). These substances can be used to control lactic acid bacteria in cheese [161]. In addition, Nisin acts as a bactericidal adjunct used in semi-hard and hard cheeses to inhibit the growth of undesired microorganisms. The European Union has authorized its use in cheese up to 12.5 mg/kg specifically for ripened cheese. Nisin has strong anti-microbial activities against a wide range of Gram positive bacteria causing food poisoning and spoilage [162]. So it works well as a natural preservative in cheese making, too. Also, some studies showed that applying it makes cheeses tastier and safer at the same time.Its use can be made during Gouda cheese ripening without influencing the level of *Lactobacilli* ([163]. Additionally, nisin is used when making Cheddar cheese to preserve it naturally instead of using artificial preservatives. This shows that nisin can be used as an option for man-made preservatives [164]. Therefore, nisin is essential for improving the microbiological quality and ensuring the safety of hard and semi-hard cheeses. The nisin-producing strains of *L. lactis* exhibit antimicrobial activity against different organisms including *Listeria monocytogenes* in matured sheep and cow milk cheeses [165]. *S. aureus* when added to pasteurized milk [166]. The cheeses that were produced using milk that contained 0.05 % (w/v) nisin were compared with control cheeses made without nisin addition. After four weeks of ripening, the physico-chemical parameters (including moisture, pH, and titrable acidity), textural parameters, and LAB (lactic acid bacteria) counts did not exhibit any significant differences between the two varieties of cheese [167]. Additionally, propionic acid is naturally present in a variety of semi-hard cheeses, particularly those that endure propionic acid fermentation. The quantity of propionic acid produced during the ripening and storage of 16 varieties of korean hard and semi-hard cheeses, as well as 40 categories of imported cheese, was measured in a study conducted by Park et al., 2016 [160]. The results indicated that propionic acid was not present in either domestic or imported firm cheeses. Nevertheless, it was identified in semi-hard cheeses imported from France, Germany, and Switzerland, as well as Chevrette from the Netherlands. The average concentration of propionic acid in these cheeses was ascertained to be 18.78 mg/kg. The concentration of 182.28 mg/kg was the highest in the smoked cheeses produced in the Netherlands. Possibly, these bacteria are used in cheesemaking, which may lead to high levels of this compound being found here. While the cheese ages, lactic acid produced by LAB is converted into different organic acids by propionic acid bacteria thus raising the pH from 5.3 to 5.8. The growth of L. monocytogenes is inhibited in Dutch-type cheeses produced from pasteurized milk by the presence of short-chain organic acids, including lactic, acetic, citric, and propionic acids, and a low pH [168]. As such, a study has been carried out to predict the growth or non-growth of *Listeria monocytogenes* in cheese with organic acids. The mean minimum inhibitory concentration of non-ionized propionic acid against the proliferation of six *L. monocytogenes* strains, evaluated within a pH range of 5.2–5.6 and a temperature of 12 °C, was determined to be 11.0 mM. Hence, propionic acid can have a significant impact on suppressing the proliferation of pathogens while cheese is maturing [168]. Propionic acid has various effects on human health. It reduces the amount of fatty acids in the liver and plasma, decreases food intake, has immunosuppressive actions, and increases tissue sensitivity to insulin [169] finally used natural because the investigation of safe natural products as alternatives to synthetic preservatives has been prompted by the rising consumer demand for natural foods and longer product shelf-life [170]. Throughout history, plants have been commonly utilized as natural additives and preservatives. In the case of cheese, dried plants, extracts, aqueous solutions, or essential oils (EOs) have frequently been incorporated. They can be utilized in cheesemaking either as additives or on the surface of the cheese to inhibit the growth of mold. Considerable focus has been placed on plant-based products as potential sources of antimicrobials for dairy products [171]. The green tea plant compound is utilized in low concentrations to safeguard foods from the production of unpleasant off-flavors. The low-fat Kalari cheese was treated by immersing it in aqueous solutions containing EGCG at concentrations of 0.05 % and 0.1 %. Comparable outcomes in terms of antioxidant activity, inhibition of microbial growth, and sensory properties (such as texture, flavor, and overall acceptability) were observed in the cheeses treated with extracts from pomegranate rind and pine needles during storage [172]. Dried rosemary's high rosmarinic, caffeic, phenolic, and flavone content makes it antibacterial. Semi-hard cheeses made from raw and pasteurized cow's milk were coated with 3 % lard and 4 % dehydrated rosemary after a 15-day ripening period. After 60 days of maturation, the cheeses' fat, ash, acidity, and protein content did not change. Only rosemary-covered cheeses had more moisture than uncovered cheeses. Due to lard's shielding, coatings increased proteolysis in

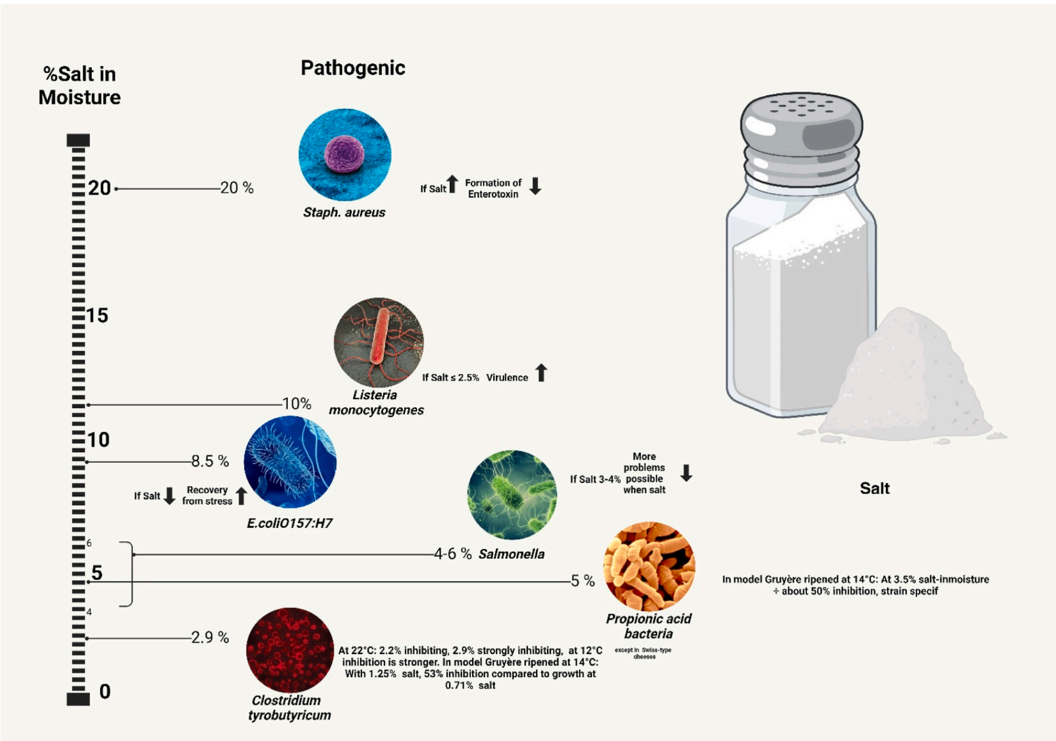

Fig. 6. Cheese typically has these salt and temperature levels.

cheeses. No color difference was seen between control and rosemary-coated cheeses. However, coated cheeses had a greener appearance, especially pasteurized cheeses. The sensory panel gave rosemary-coated raw milk cheeses the highest scores for their subtle fragrance and piquant taste [173]. Anti-oxidant Activity was mixed with 0.2 % clove (Syzygium aromaticum), 0.5 % black cumin (Nigella sativa), and black pepper (Piper nigrum) powder. The cheeses were refrigerated at 7 °C. After eight weeks,

Table 5
The primary results of research on the impact of decreasing or replacing salt on the physical, chemical, and sensory characteristics of cheese [182].

Type of cheeses	Textural and functional properties	Physicochemical properties	Sensory properties
Cheddar	-Decreases in firmness, hardness, toughness, and shortness/crumbliness were observed with reduced NaCl content and longer ripening time.-With equal moisture content, salt reduction did not affect cheese firmness or shortness, but the highest salt level (6.0 % S/M) led to a longer cheese texture. – Salt reduction below critical levels (e.g., <1.2 %) affects cooking quality.	-Cheeses with a low salt-to-moisture ratio contain less lactic acid and more galactose. -Reducing sodium and increasing potassium levels in the cheese result in elevated lactic acid concentration. -Unsalted cheeses have lower pH levels than salted cheeses containing NaCl, KCl, or a combination of NaCl/KCl.	-An optimal salt-to-moisture ratio of 4–6 is suggested for enhancing Cheddar cheese flavor and minimizing excessive proteolysis and bitterness. -The decrease in salt/moisture content from 4.9 % to 3.5 % did not have a significant impact on the flavor and texture. -Cheese with reduced NaCl content showed diminished flavor development and increased bitterness.
Mozzarella	-Cheeses containing 1.6 % NaCl had higher transition temperature (tan d 1), as well as increased elasticity and stretching resistance. -The decrease in salt concentration from 1.9 % to 0.7 % improved the flowability. -An increase in NaCl content from 1 % to 2 % resulted in a decrease in the cheese's melting point. - Sodium can interact with calcium within the casein matrix, which may improve the cheese's capacity to achieve a firmer texture.	- High salt concentrations may reduce the shelf life of Mozzarella cheese by potentially causing the solubilization of cheese casein. - Cheeses with elevated salt levels typically exhibit reduced moisture content as a result of moisture depletion during salt absorption. - Cheeses made with NaCl/KCl mixtures had similar proteolysis rates to those made with NaCl alone. -Adding emulsifying salts to processed mozzarella cheese affects its hardness, casein dissociation, and pH.	-Substituting KCl for NaCl should not exceed a 25 % ratio, irrespective of the metallic test. - Increased salt levels in Mozzarella cheese can result in reduced ability to melt and form strings compared to cheeses with lower salt content. - Elevated salt concentrations can alter the taste characteristics of Mozzarella cheese, potentially leading to an intensified perception of bitterness.
Muenster	- The melting of cheese was not impacted by the increase in NaCl content from 0.1 to 2.2 %. - Research suggests that cheese hardness may increase with lower fat content, emphasizing the complex relationship between salt, fat, and texture in cheesemaking. - Salt above 0.5 % increases cheese hardness and decreases cohesiveness. Ionic strength increases with salt content, explaining these variations.Increased ionic strength affects protein interactions on multiple levels.	- Adding salt to Muenster cheese changes its protein interactions, resulting in enhanced hydration and expansion of the protein matrix. - Calcium content decreased as potassium chloride content increased. - Cheese pH was not impacted by the rise in NaCl content. - Adding NaCl to cheese did not affect the solubility of calcium.	- Salt changes the flavor of Muenster cheese. Lower salt cheeses like Swiss and fresh mozzarella are not expected to be salty, and higher salt content may reduce flavor and characteristics. - A cheese with less than 1.5 % salt may taste less salty, while one with more than 1.8 % may taste too salty. Muenster cheese, an intermediate salted cheese (1.5–1.8 % salt), does not always taste salty, but lowering its salt content below this range could change its taste.
Cantal	-Reducing NaCl concentration and increasing KCl substitution resulted in lower melting and congealing points. - Rheological data for cantal showed that reducing NaCl content led to a decrease in fat melting temperature, whereas replacing it with KCl tended to increase this temperature compared to the control. - Reducing NaCl content may affect cheeses' thermal behavior and molecular structure more than KCl substitution. This is likely due to protein-protein and water-protein interactions that alter cheese matrix structure.	- Reductions of NaCl at 25 % and 50 % did not impact the rates of proteolysis. - The calcium content in cheeses with varying levels of added sodium chloride (ranging from 1 % to 2 %) remained constant. - A comparison was made between the effects of adding KCl and NaCl salts at concentrations of 1–2% for 5 days and 15 days on mineral content. Calcium, potassium, and phosphorus levels increased while magnesium levels decreased, along with a reduction in moisture content.	- Reducing salt in Cantal cheese can have various effects on its sensory properties. - Reducing salt concentration can lead to a decline in flavor quality.
Prato	-A 25 % reduction in salt content did not affect proteolysis and sensory acceptance, but a 50 % reduction resulted in less firm and less acceptable cheese. -use of salt substitutes and flavor enhancers can potentially mitigate the negative effects of salt reduction on the texture properties of Prato cheese.	-Replace 40 % of sodium chloride with KCl, Sub4salt®, and Salona™. During ripening, physicochemical characteristics, pH, proteolysis indexes, melting capacity, and texture profile changed significantly, but there were no significant differences. More sodium reduction was seen in brine-salted cheeses using KCl (28.16 %) and Salona™ (34.94 %).	-Adding arginine improved the flavor and appearance of low sodium cheese. -Cheeses with a 50 % reduction in NaCl were found to be less firm and less sensorially acceptable compared to the control cheese and the cheese with a 25 % reduction in salt. −25 % reduction in salt content did not affect proteolysis or sensory acceptance, although a 50 % reduction resulted in less firm and less acceptable cheese -the overall acceptance of Prato cheese can be influenced by the level of somatic cells in the milk used, with lower levels associated with better acceptance.

clove-flavored cheeses had the highest AA (aroma activity), followed by black cumin and black pepper cheeses. However, black pepper cheeses scored highest for sensory acceptance, followed by black cumin and clove cheeses [174].

7.4.4. Salt content

The salt content is essential for inhibiting the proliferation of undesirable microorganisms in hard and semi-hard cheeses. Salt is a significant barrier to bacteria growth in cheese, effectively inhibiting their development and ensuring the safety and quality of the end product. Cheeses which have a moisture content of between 49 % and 56 % are termed as hard cheeses whereas the ones that contain 54%–69 % of moisture fall under the semi-hard category [46]. Certain types of cheese are aged due to bacteria that grow on them. These cheeses have low moisture content, so they age slowly. Using packaging materials with low gas permeability can create an anaerobic environment, which enhances their safety and extends their shelf-life [175]. In addition, salt serves the dual purpose of enhancing the taste of the cheese and facilitating the removal of whey by regulating its expulsion and causing the curds to contract, thus impeding or stopping the proliferation of bacterial cultures. Hence, it is crucial to maintain an optimal salt content to inhibit the proliferation of unwanted microorganisms and guarantee the safety and quality of hard and semi-hard cheeses [176]. Salt is essential for cheese safety and quality. Salt alone does not prevent pathogenic bacteria from growing, but it does when combined with other factors. This is especially important for unpasteurized milk cheeses. *Shiga-toxin*-producing *Escherichia coli* O157:H7 can survive in 8.5 % salt-in-moisture. They tolerate salt moderately. This serotype recovers faster from stress at low salt levels. Little is known about how salt affects other disease-causing *E. coli* strains. *Staphylococcus aureus* can survive in 20 % salt-in-moisture environments [177]. It grows best between 0.5 and 4.0 % salt, while higher concentrations slow it down. *Staphylococcal enterotoxin* (SE) production decreases with salt concentration and stops at 10 % for various SEs. *Listeria* species can survive in salt concentrations up to 10 % and salt-in-moisture levels up to 25 %. *Listeria monocytogenes* grew more virulently in salt concentrations below 2.5 %. A 4–6% salt solution in moisture at 8–12 °C prevents *salmonella* growth [178]. Cheese typically has these salt and temperature levels (Fig. 6). In addition, when salt (or any solute) is dissolved in water, water activity decreases. Cheese salt levels range from 0.4 % in Emmental to 5 % in Blue. The amount of salt dissolved in cheese's water (SM) determines its inhibitory effect, not its concentration. Cheddar cheese has 4–6% moisture. Most cheeses are brine-salted, but cheddar is dry-salted. Brine-salted cheeses have a salt gradient and higher salt concentration on the outside than inside. This gradient decreases as cheese ripens. Brined cheeses have salty outer layers, so surface microorganisms must be salt-tolerant [179]. Most *coryneforms*, *micrococci*, and *staphylococci* thrive in 10–15 % NaCl. *P. camemberti* grows without much inhibition in 10 % NaCl, but some strains of P. roqueforti can tolerate 20 %. Salt sensitivity is high in *Geotrichum candidum*. The organism may grow slowly in 1 % NaCl and stop completely in 6 % NaCl. Therefore, excessive brining will prevent its growth on cheese. Some G. candidum cells thrive in salt, so it is intentionally added to surface-ripened cheeses [43]. But on the other hand E. Dugat-Bony et al. (2019) examined the microbiological and biochemical effects of reducing sodium chloride (NaCl) in experimental surface-ripened cheese. Over 27 days, a control cheese (1.8 % NaCl) and a reduced-NaCl cheese (1.3 % NaCl) were sampled weekly. Reduced NaCl content caused Debaryomyces hansenii to grow less and Hafnia alvei to grow more [180]. Changes in proteolytic kinetics, volatile aroma compound profiles, and biogenic amine production occurred. Finally, low-salt cheese had more *Pseudomonas* fragi spoilage microorganisms. In the other study examined the effects of reducing sodium chloride by 20 % or replacing it with potassium chloride in soft ("Camembert"-type) and semi-hard ("Reblochon"-type) cheeses. Analysis included physicochemical and biochemical composition, microbial counts, 16S rRNA gene metabarcoding and metatranscriptomic analysis, volatile aroma compounds, and sensory analysis. Soft cheese salt affected proteolysis after 21 days of ripening. Ribonucleic acid (RNA) sequencing showed that reduced salt cheeses upregulated *G. candidum* and downregulated *P. camemberti* compared to controls. Due to higher alcohol and ester compounds, low-salt cheeses had a stronger global odor and taste. The biochemical parameters, sensory characteristics, and microbial population of semi-hard cheeses did not change during the 21-day ripening period due to salt content changes. Salt did not affect Yarrowia lipolytica growth in soft cheeses [180,181]. In contrast, reducing salt in semi-hard cheeses increased Pseudomonas growth. Protein and fat breakdown in cheese increased due to proteolysis and lipolysis. Cheese variety greatly affects the effect of reducing salt. Table 5 presents the main findings of studies investigating the impact of reducing or substituting salt on the physical and chemical characteristics of cheese, as well as sensory properties.

7.4.5. Storage temperature

In order to inhibit the proliferation of undesirable microorganisms in semi-hard cheeses, it is crucial to uphold suitable storage temperatures. Utilizing low-temperature methods for processing and storing cheese can extend its preservation time, potentially reaching or exceeding one year [77]. This has advantages for both the financial viability of the dairy industry and the environment. Sub-zero temperatures can impede the proliferation of microorganisms, thereby promoting the development of healthier aged cheeses. However, to prevent frostbite, it is imperative to employ appropriate packaging using impermeable materials like plastics. Storing cheese at room temperature can expedite the ripening process, whereas refrigeration inhibits the growth and activity of lactic acid bacteria (LAB) and other microorganisms [183]. Cheddar-type cheeses are typically cured or aged at temperatures as high as 15.6 °C, while Swiss cheese is held at a temperature range of 22.2–23.3 °C for 4–8 weeks to develop its distinctive characteristics. Nevertheless, elevated storage temperatures beyond refrigeration can trigger alterations in the composition of volatile compounds and impact the overall quality of the cheese [184]. The optimal storage temperature for cheese varies depending on the type. However, for semi-hard cheeses such as Cheddar or Gouda, a temperature of approximately 10 °C (50 °F) is generally recommended [185]. Controlling humidity and temperature in storage is crucial for delicately decelerating the aging process, managing the growth of pathogens, and averting quality defects. Preservation of food is made possible for a long period through cryopreservation, at the same time maintains its nutritional value. Here, the freezing point of the food is lowered which leads to ice crystal development preventing any growth of bacteria or any biochemical reactions taking place. Crystal formation may damage the structure of the food [186]. The process of hardening cheese is well known in the food industry because it does have an effect. For example, freezing and storing cheese at single digits or a few degrees above zero significantly affects the quality characteristics of these categories of cheese [187]. Multiple cryogenic storage experiments have been conducted, yielding limited achievements. The literature has discussed the practice of freezing milk or concentrated milk before cheesemaking. However, it has been observed that freezing at temperatures of −15 and −27 °C leads to noticeable sensory defects in the resulting cheeses. The total number of viable organisms and coliforms decreases more rapidly at a temperature of −15 °C compared to −27 °C [188]. Nevertheless, certain studies indicate that freezing sheep milk at temperatures between −15 and −25 °C for a duration of 6 months does not have any impact on cheese yield or composition, and can still result in the production of high-quality cheese [189]. Freezing was discovered to cause substantial alterations in the microstructure of Crottin de Chavignol goat cheese and resulted in a 2 log unit decrease in the total count of lactic acid bacteria (LAB) [190]. An alternative method to prolong the shelf-life of ripened cheeses is by freezing them, which aims to hinder or decrease enzyme activities and chemical reactions that cause over-ripening [143]. The findings for Motal cheese indicated that storing it at a temperature of −18 °C effectively minimized the production of excessive free fatty acids (FFAs) and preserved the volatile compounds. Additionally, there was only a slight decrease in the count of lactic acid bacteria (LAB), which helped maintain the quality of the product and prolonged its shelf-life [187]. On the other hand, negligible alterations in taste were noted in a particular type of goat cheese following a storage period of six months at a temperature of −20 °C. After being stored at a temperature of −20 °C for five years, the flavor of the cheese remained largely unaffected, with only a noticeable change in texture, resulting in a more grainy and sticky consistency [191]. The water that is bound to the protein does not form crystals at a temperature of −20 °C, and its physical characteristics remain unaltered [192]. Therefore, this temperature is optimal for preserving the protein structure, while other freezing methods lead to inferior cheese quality due to chemical reactions caused by the abundance of unfrozen solution and the freezing of bound water. The study examined the impact of two freezing rates (−20 °C and −82 °C) and a frozen storage time of 9 months at −20 °C on the characteristics of an ewe's milk cheese after 90 days of ripening. The freezing treatments did not have a noticeable impact on the chemical and microbiological properties of the cheeses [193]. However, the slowly frozen cheeses exhibited a slightly higher level of graininess. No notable disparities were observed in total viable counts and the presence of *enterococci*, *Enterobacteriaceae*, *coliforms*, *staphylococci*, molds/yeasts, and *micrococci* when comparing the control cheeses and the two freezing rates [194]. *Leuconostoc* and *lactobacilli* exhibited a gradual decline, which became more pronounced towards the conclusion of the 9-month storage period. The study determined that the chemical and microbiological composition, as well as the sensory properties of the cheeses, remained unchanged after being stored at a temperature of −20 °C for a period of six months. Comparable findings were reported for a Manchego-style cheese that had been aged for 180 days and stored at a temperature of −20 °C for a duration of six months. The microbiological analysis showed comparable levels of total viable microorganisms, lactic acid bacteria (LAB), and molds and yeasts. However, the counts of *micrococci* and *staphylococci* decreased during the frozen storage period. Several of these specific freezing techniques are currently in the stage of industrial development, and require a significant investment. Hence, it is crucial to evaluate the trade-off between the quality and cost of the product when applying these preservation techniques in the dairy industry [186,195].

8. Packaging

Cheeses are prone to microbial contamination due to their favorable acidity conditions and high-water activity [196]. The majority of studies on cheese storage and shelf-life focus on issues arising from microbial contamination. Moreover, the absence of a packaging barrier in certain types of cheeses can lead to significant moisture loss, which can contribute to increased hardness and undesirable sensory characteristics [197]. Effective packaging is widely recognized as a highly beneficial method for preventing the chemical, physical, biochemical, and microbiological degradation of cheese. It also extends the cheese's shelf life and enhances its overall quality. These requirements could be fulfilled by synthetic packaging films. Nevertheless, the non-biodegradability of synthetic films has sparked significant environmental concerns. Additionally, consumer demand for safe food products and extended shelf life has led to increased focus on bio-nanocomposite films [198]. Biopolymeric films exhibit lower tensile strength compared to conventional plastic films, but their elongation-at-break values are similar to those of typical plastic coatings [199]. In addition, certain biopolymeric coatings and films possess excellent oxygen barrier properties, with their water vapor permeability being generally higher than that of conventional plastic films, excluding lipid-based edible films [200].

8.1. Edible packaging

Edible films and coatings made from biodegradable materials such as polysaccharides, lipids, waxes, and proteins can preserve the quality of cheese by serving as a semipermeable barrier to water vapor, oxygen, and carbon dioxide, preventing water loss [201]. Moreover, cheese could be put in fatty material like plastic while in suspended form to prevent it from losing its moisture. Additionally edible films and coatings may serve as carriers for antioxidant and antimicrobial agents to prevent lipid oxidation and microbial growth on cheese [202]. They can act as a conveyance for bioactive compounds with antioxidative and antimicrobial activities which regulate their diffusion into the cheese thus improving its keeping quality. Through possessing barrier, antioxidant and antimicrobial characteristics coatings extend shelf-life of cheese products by protecting them against environmental influences [203]. Guardin (2015) found that using whey protein isolate (WPI) to create antimicrobial and antioxidant edible films with OEO allowed queso Blanco cheese to remain refrigerated for up to one month without spoilage [204]. Cerqueira et al. (2010) investigated the effects of various storage temperatures on a semi-hard cheese coated with chitosan and galactomannan from Gleditsia triacanthos seeds [205]. Overall we found out that when the cheese was coated it usually lost less weight, changed color less often, became softer and allowed less gas exchange with its environment. The interesting thing about this research is that while most cheeses have lower levels of moisture after being covered in such a way, the samples contained more water than the control group. 120 days into ageing it became clear that lactic acid bacteria were thriving better in these conditions while fungi struggled more– their growth decreased significantly over time compared to other treatments tested within RAS system [205]. Although there was also some improvement noted for sensory properties when using chitosan alone or combined with another compound like galactomannans, our panelists still rated them lower than those treated by RAS technology only – which means we need to keep working on finding out what exactly makes composite films work better than single polymers [205]. In addition, Berti et al. (2019) using ripening of Gouda cheese treated with an edible coating based on tapioca starch and glycerol containing natamycin and nisin. This study compared the effects of using CNANI and GNANI coatings on Gouda cheese to prevent surface contamination in the cheese industry. Results showed that while both coatings did not affect the cheese's physicochemical properties or the growth of Lactobacilli during ripening, cheese covered with GNANI was harder, gummier, and chewier than cheese covered with CNANI after storage. Additionally, GNANI provided a better barrier against external contamination during ripening compared to CNANI for the growth of a mixed culture of *Saccharomyces cereviseae* and *Listeria innocua* [206]. Moreover, in another study on alginate edible coating with oregano and rosemary EO for fresh cheese. Analyzing microbial content, centesimal composition, texture (shear force), instrumental color, sensory acceptance, and mass loss was practical. Coatings with rosemary essential oil (EO) reduced Coliforms (35 °C) in storage, improving cheese microbiological quality. All edible coating samples passed sensory evaluation (Acceptance Index >77 %), with oregano essential oil standing out. Alternatively, this coating could improve fresh cheese quality technologically [206]. In the other hand, Ramos et al. in the study, Antimicrobial edible coatings were tested as a 60-day cheese packaging alternative to nonedible coatings. Whey protein isolate, glycerol, guar gum, sunflower oil, Tween 20, and antimicrobial compounds like natamycin, lactic acid, and chitooligosaccharides formed the coatings. Cheese coating reduced water loss by 10 %, hardness, and color change. Salt and fat were unaffected. The antimicrobial edible coatings also prevented harmful microorganisms but allowed lactic acid bacteria to grow during storage. Non-edible commercial coatings only inhibited molds and yeasts. The edible natamycin-lactic acid coating outperformed the other antimicrobial coatings in taste. These food-grade antimicrobial coatings can be eaten with cheese, giving them an advantage over non-edible coatings [207], in addition kaves et all in the study An edible coating (WPIG) was made with 1.5 % sorbitol, 5 % WPI, 0.5 % alginate, and 1.5 % ginger essential oil. Kashar cheese was contaminated with 106 cfu/mL *Escherichia coli* O157:H7 and *Staphylococcus aureus*. The edible coating was applied to Kashar samples and stored at 4 °C for 30 days. Antimicrobial and physical-chemical properties were assessed on storage days 1, 7, 15, and 30. WPI's water barrier properties were improved by 1.5 % (v/v) ginger essential oil, which had antimicrobial effects. In time, *Escherichia coli* O157:H7 and *Staphylococcus aureus* increased in uncoated samples but decreased in coated samples [208]. The study investigated the effects of chitosan and chitosan/whey protein on the chemical, microbial, and sensory properties of Göbek Kashar cheese at 3, 30, 60, and 90 days of ripening. Significant differences in microbiological and chemical changes were observed between samples during ripening ($p < 0.05$). Cheese coated with an edible layer had notably lower mold counts compared to uncoated samples. On the 60th and 90th days of storage, the control sample had the highest mold count at 4.20 Log CFU/g, while other samples had less than 1 Log CFU/g. After storage, all samples had higher water-soluble nitrogen and ripening index. Cheeses had similar salt and fat content after 90 days of storage. Edible coatings improved cheese taste. In sensory analysis, panelists preferred cheese C and chitosan-coated cheese samples, while chitosan/whey protein film-coated cheese samples scored lowest. This study shows that coatings can improve cheese

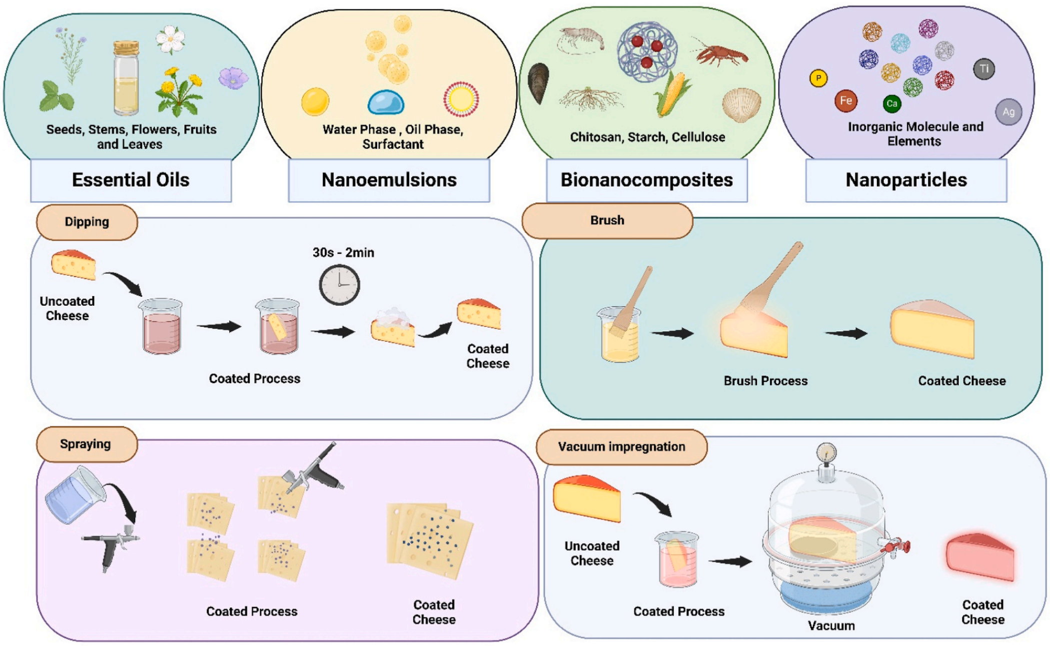

Fig. 7. Various types of coatings and the corresponding coating materials utilized and depleted.

quality with age [209]. Other proteins, such as caseins [210], and polysaccharides can preserve cheese varieties. Examples include starch edible films in Port Salut [211] and Cheddar cheese samples [212], galactomannan in Saloio cheese [205], cellulose in Gorgonzola cheese [211], carboxymethylcellulose in semi-hard Paipa cheese [213], and alginates and carrageenans in other cheeses [214]. Fig. 7 illustrates various types of coatings and the corresponding coating materials utilized and depleted.

8.2. Active packaging

Active packaging technologies for hard and semi-hard cheeses often incorporate antimicrobial agents to inhibit the growth of harmful microorganisms and ensure a longer shelf life for the products. One example of such an antimicrobial agent is natamycin, which is authorized for use as a surface treatment in hard, semi-hard, and semi-soft cheeses at a maximum level of 1 mg/dm2 surface [215]. Additionally, other antimicrobial substances such as silver nanoparticles, essential oils, or natural extracts can be integrated into cheese packaging to achieve the same purpose. In addition, in the study Zein and zein-wax composite films with different release profiles for lysozyme and a mixture of lysozyme, catechin, and gallic acid were tested on cold-stored fresh Kashar cheese contaminated with *Listeria monocytogenes* ATCC 7644 for antimicrobial and antioxidant properties For 8 weeks at 4 °C, lysosome-containing films inhibited L. monocytogenes growth in Kashar cheese. Only the zein-wax composite films with consistent lysozyme release rates reduced the cheese samples' initial microbial load by 0.4 log cycles. Catechin and gallic acid increased film antimicrobial activity against *L. monocytogenes* in vitro but not in cheese. Cheese oxidation was prevented by catechin and gallic acid films [202]. Active packaging can also have oxygen absorbing properties. On the other hand, a study reported that a microbiological oxygen scavenging material containing *Lactococcus lactis* strain reduced oxygen levels in cheese packs while producing minimal acetoin and diacetyl. Graviera cheese packed with both an oxygen scavenger and ethanol emitter had lower microbial growth compared to packages with 100 % nitrogen. These combined packages also showed an extended sensory shelf-life [216]. Negamold®, an ethanol vapor sachet created by Nippon Kayalan firm in Japan, was initially designed for meat products. Freund corporation in Japan later integrated an oxygen absorber with Negamold® for cheese packaging [217]. In addition, active packaging can have Films containing free radical scavengers or antioxidant properties such as many study about this section A gelatin-chitosan edible film containing Boldo herb extract exhibited antioxidant and antimicrobial properties, preserving sliced Prato cheese by inhibiting psychrotrophs [218]. Other natural antioxidants such as green tea extract, catechins, and rosemary extract have been studied for their antioxidant properties in cheese packaging. However, a significant challenge with using antioxidant-infused films in cheese packaging is ensuring that the diffusion rate of antioxidants aligns with the needs of the cheese [219]. The primary concern in incorporating natural antioxidants into continuous film production through extrusion is their stability and thermal degradation.

8.3. Intelligent packaging

Packaging for hard and semi-hard cheese should take into account factors such as ripening time, temperature, and cheese surface area to volume ratio. Very hard, extra hard, hard, and semi-hard cheeses have varying moisture content and require different packaging materials to maintain their texture and prevent moisture loss [220]. Some packaging technologies for cheese include time-temperature indicators, gas sensors, and smart packaging that can monitor and communicate important information about the cheese product [221]. Design elements to consider for cheese packaging include color palette, cheese type, nutritional information, and storage instructions. Preservation studies are also important for maintaining and increasing the shelf-life of hard and semi-hard cheeses. In this section have many research about intelligent packaging the first is about gas indicators in the study monitoring oxygen levels is crucial for maintaining cheese quality and safety from production to shelf-life [222]. Redox dye-based oxygen indicators have been documented to non-destructively indicate the package integrity and status of modified atmosphere packaging (MAP) in food

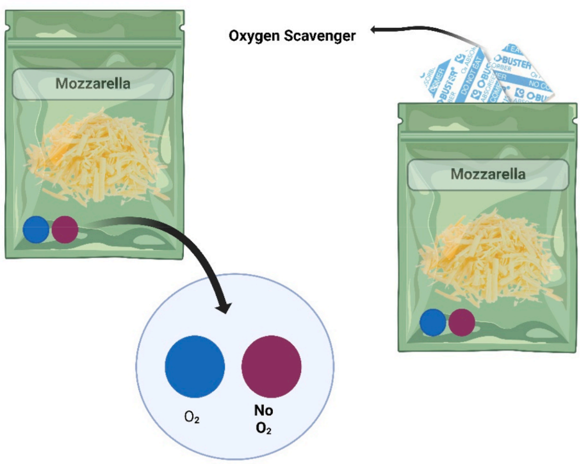

Fig. 8. Mozzarella cheese package containing an oxygen indicator, oxygen scavenger, and dye-based oxygen sensor.

[223]. Fig. 8 shows a diagram of a Mozzarella cheese package containing an oxygen indicator, oxygen scavenger, and dye-based oxygen sensor. A fluorescent oxygen sensor made with platinum octaethylporphyrin-ketone (PtOEPK), a phosphorescent dye sensitive to oxygen, detected changes in oxygen levels in MAP cheddar cheese for 4 months. The sensor's sensitivity ranges from 0.02 % to 100 % oxygen. An opportunity arose to evaluate cheese quality by utilizing a colorimetric oxygen sensor due to the correlation observed between oxygen concentration and microbial growth [221]. A biodegradable chitosan film with pomegranate peels/Melissa officinalis essential oil showed antimicrobial properties and anthocyanins functionality as a spoilage indicator. The film changed color from blue to red in response to pH changes in cream cheese during spoilage [224]. A chromogenic array pattern using pH dyes accurately classified five types of blue cheese: Roquefort, Blue Stilton, blue cheese with leaves, blue cheese spread, and Cheddar. fourth Cheese ripening indicator Methods, processes, or sensors to detect metabolites, particularly volatiles, or chemical breakdown products from glycolysis, proteolysis, and lipolysis to measure cheese maturity or age [225]. On the other hand, an e-nose was used to analyze volatile compounds in packaged ripened cheese (Crescenza) to determine its shelf life. The data helped determine cheese shelf life [226]. Tavaria, Ferreira, and Malcata (2004) measured free fatty acids, acetic acid, isobutyric acid, and isovaleric acid in Serra da Estrela cheese over 180 days. Volatile fatty acids indicate cheese ripeness and when to eat it. Industrial models using infrared reflectance spectra can predict Cheddar and Camembert cheese ripening and sensory characteristics within a day. These models use alcohol and amide absorbance changes [227]. Fifth time temperature indicators Temperature affects microbial growth, enzyme activity, and chemical reactions, so a food product's "biological use by date" or "chemical best before date" depends on its temperature exposure history. Time temperature indicators (TTIs) record food product temperatures over time [228].

8.4. Modified atmosphere packaging (MAP)

To preserve cheese, it is important to change the packaging atmosphere with modified atmosphere packaging (MAP). Hard and semi-hard cheeses last longer when preserved using MAP. The quality and sensory properties are also maintained with MAP while the shelf life of cheese is extended through the creation of an atmosphere different from air [229]. MAP applies refrigeration temperatures

Table 6
The effect of packaging types on the characteristics of hard and semi-hard cheese.

Main findings	Ref.
Modified atmosphere packaging (MAP) extended the shelf-life of cheese due to CO_2 inhibiting spoilage microorganisms.	[235]
Mathematical models successfully predicted microbial growth in Minas Frescal cheese under different modified atmosphere packaging, with a significant reduction in the growth rate of psychrotrophs and lactic acid bacteria with higher CO_2 levels. The sensitivity to CO_2 was similar in psychrotrophs and lactic acid bacteria, indicating a consistent effect of CO_2 on microbial growth in the cheese. The maximum growth rate of microorganisms was drastically reduced under modified atmosphere packaging with higher CO_2 levels, highlighting the importance of CO_2 in controlling microbial growth in MF cheese.	[236]
Modified atmospheres alter lipolysis and proteolysis, leading to the accumulation of smoke-derived compounds that negatively impact flavor. Vacuum packaging is the most effective method for preserving sensory quality of San Simón da Costa smoked semi-hard cow's milk cheeses.	[237]
Modified atmosphere packaging with 100 % CO_2 effectively inhibited microbial growth in Kashar cheese. Both 40 % and 100 % CO_2 can extend the shelf life of fresh Kashar cheese.	[238]
Validation of the model through a packaging experiment with semihard cheese, demonstrating its utility as a tool for optimizing modified atmosphere packaging. The model can be used to estimate and manage changes in carbon dioxide levels in packaging due to various conditions.	[239]
Vacuum packaging and modified atmosphere packaging improved the quality and shelf life of Crottin de Chavignol type goat cheese. Vacuum packaging led to higher hardness, chewiness, and gumminess values compared to modified atmosphere packaging, with taste scores of vacuum-packaged cheese samples dropping below the acceptability limit due to oxidized flavor at 15 weeks.	[240]
Modified Atmosphere Packaging had a significant impact on the physicochemical and sensorial properties of Sepet cheese samples, with specific conditions providing better preservation. Sensory analysis showed that packaging conditions influenced the shelf-life of the cheese.	[241]
100 % CO_2 and 100 % N_2 were the most effective in inhibiting bacterial growth and extending shelf-life. MAP can effectively extend the shelf-life of Domiati cheese while preserving sensory quality.	[231]
The main findings of the study include the effectiveness of 40 % CO_2/60 % N_2 and 50 % CO_2/50 % N_2 packaging conditions in retaining good sensory characteristics in Cameros cheese, particularly in taste and odor, while cheeses packaged under vacuum showed rapid deterioration in surface appearance and texture. The proposed methodology allowed for the quantification of sensory differences between different packaging conditions.	[242]
The main findings include the impact of light exposure on semi-hard cheese color, the effect of different packaging atmospheres on cheese lightness, the sensory characterization of cheeses stored in different conditions, and the volatile compounds present in cheeses stored in 100 % CO_2 and exposed to light.	[243]
Both the active system Humidipak® and the microperforated film were successful in extending the shelf-life of the cheese by reducing water loss. The sensory analysis indicated that the microperforated film maintained the initial characteristics of the cheese, with minimal changes observed over the storage period. The results suggest that both packaging systems offer promising solutions for preserving the quality and extending the shelf-life of the Saloio cheese.	[244]
Migration of volatile compounds from PLA into cheese was minimal and below critical levels. Recommendations include dark storage or use of non-transparent materials to protect against lipid oxidation and moisture loss when using PLA for packaging semi-hard cheeses. Oxygen scavengers reduced lipid oxidation, but not as effectively as storing the products in the dark.	[245]
The combination of active coating and MAP improved Fior di Latte cheese preservation, extending shelf life to more than 3 days. Coating with natural antimicrobials in MAP conditions was an effective strategy for prolonging shelf life. Monitoring various parameters over 8 days at 10 °C provided insights into quality changes.	[246]

and gas mixtures of CO_2, N_2 and O_2 to hard and semi-hard cheeses. CO_2 stops microorganisms such as spoilage bacteria while N2 acts as an inert filler gas to keep the package from collapsing [230]. Cheese appearance, flavor, color, pH, and texture are among the things that MAP treatments affect in various ratios including CO_2/N_2 gas combinations, vacuum packaging, and aerobic packaging [231]. Research indicates that the employment of MAP technology can prolong the shelf-time of firm and semi-firm types of cheese as well as retain their taste [232].

8.5. Vacuum packaging

Vacuum packaging is a method used to preserve hard and semi-hard cheeses, creating a vacuum that prevents spoilage germs and extends shelf life [31]. Vacuum packaging combined with other preservation methods such as freezing and salting enhances the keeping quality of cheese [45]. This anaerobic condition retards microorganisms growth while reducing lipid oxidation. Additionally, vacuum sealing helps to maintain color as well as flavor by preventing dehydration or weight loss which may occur during storage under normal atmospheric conditions. Even though there are very few demerits of using this method in preserving dairy products however, some researchers argue that texture changes could be observed when packaging cheese under vacuum [233]. On the other hand, not all types of cheese can be packed in a vacuum since it may affect their structure leading to them not being acceptable for consumption. Therefore, each type of cheese should be kept in mind when selecting an appropriate package that will ensure its maximum preservation. As a result, matured cheeses remain safe and delicious if stored using these packages. Vacuum packaging reduces food waste and extends cheese shelf life, helping the food chain [234]. Table 6 summarizes research on how different packaging types affect the quality and shelf life of hard and semi-hard cheeses.

9. Artificial intelligence in cheese quality assessment and production

Artificial intelligence (AI) is rapidly transforming the cheese industry by improving the assessment and production of cheese quality. Key AI applications include machine learning models, neural networks, computer vision systems (CVS), and advanced sensory technologies, all of which are central to ensuring consistency, efficiency, and sustainability in cheese production. One significant application is the use of machine learning algorithms, such as feedforward artificial neural networks (ANNs), to predict the shelf life and quality of cheese. These models analyze critical input parameters like soluble nitrogen, pH, and microbial counts. By employing Bayesian regularization-based backpropagation algorithms, these models provide high prediction accuracy, helping manufacturers optimize storage and reduce waste [247]. Computer vision systems (CVS) are essential for real-time cheese quality assessment,

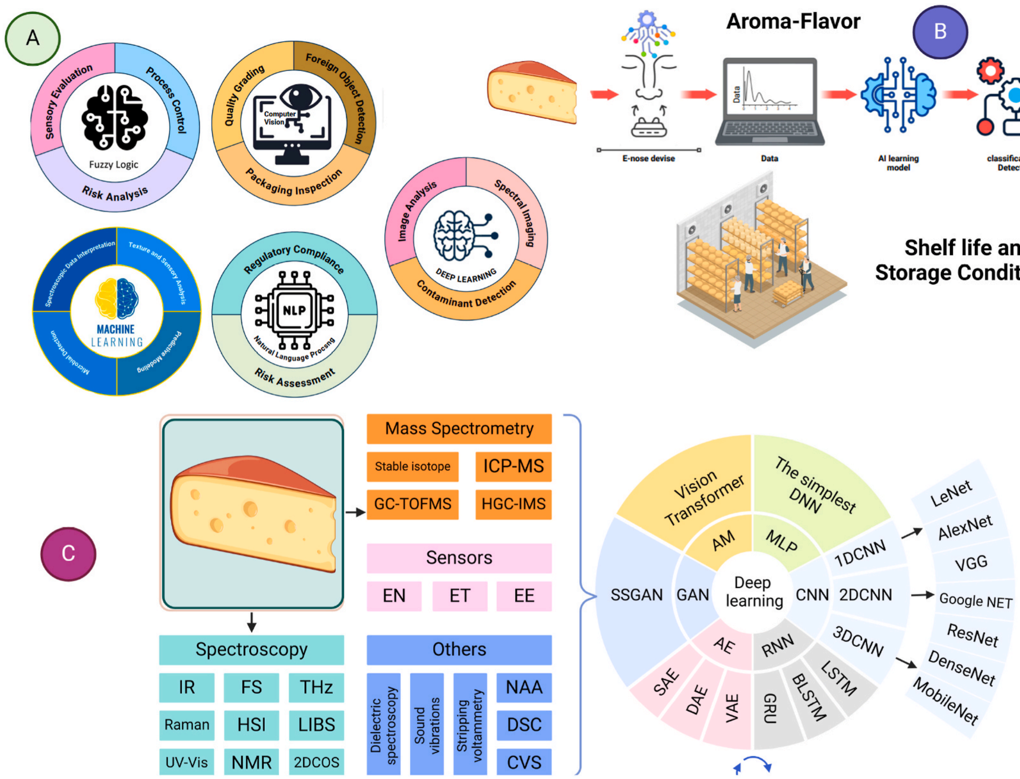

Fig. 9. (A) AI-based technologies in Cheese industry (B) Detection methods for quality and classification by E-nose with AI. (C) Overview of different detection technologies along with deep learning models for cheese quality and safety.

utilizing digital imaging technologies and sensors to evaluate characteristics such as texture, color, and structural integrity. CVS has successfully been applied in assessing the ripeness of Swiss-type cheeses by monitoring the formation of "eyes" and evaluating gas holes in other varieties, such as "Queijo de Nisa," where changes in these patterns correlate with moisture and pH variations during ripening [248]. Another study used supervised machine learning techniques to classify 10 Swiss cheese varieties based on their free volatile carboxylic acids (FVCA) profiles. Both Extra Trees (ET) and Random Forest (RF) classifiers achieved over 90 % accuracy, with SHapley Additive Explanations (SHAP) values identifying C1, C3, C6, and iso-C4 as the most important features for classification, demonstrating how machine learning models can effectively differentiate cheese varieties based on chemical composition [249].AI techniques, including computer vision and machine learning, have also been applied to monitor cheese quality during the ripening process. These methods automate the classification of ripeness levels, improving product consistency and reducing human errors [250,251]. Loddo et al. (2022) developed a non-invasive system using computer vision and machine learning to monitor cheese ripeness at various stages (18, 22, 24, and 30 days). The study employed deep features from convolutional neural networks (CNNs), such as ResNet-101 and DenseNet-201, to classify ripeness with high accuracy [252].Near-Infrared (NIR) spectroscopy, combined with AI, is proving effective in predicting the physico-chemical properties of cheese, such as fat content and moisture during production and ripening. This method offers a non-invasive alternative to traditional testing techniques [250,253]In addition, ultrasound technology, combined with AI, is used to assess internal cheese structures without damaging the product, offering insights into the ripening process for cheeses such as Swiss and Cheddar varieties [248].Artificial neural networks (ANNs) have also been employed to predict the ripening stages of cheeses by analyzing complex chemical, microbial, and sensory data. Studies demonstrated that ANN models achieved 100 % accuracy in predicting the ripening stage of Turkish white brined cheese based on NIR data [254]. Moreover, magnetic resonance imaging (MRI) technology has been used for quality control in blue-veined cheeses, allowing non-invasive assessments of mold distribution and ripening defects [255].An electronic nose (e-nose) system has also been employed to monitor the ripening of Danish blue cheese. AI-driven multivariate analysis models accurately classified cheese samples at different ripening stages, providing an objective and automated quality assessment method without requiring expensive equipment or extensive human training [256].Lastly, convolutional neural networks (CNNs) and vision transformers (ViTs) were applied to extract features from cheese images, processed through machine learning algorithms to predict ripeness levels. A hierarchical classification method effectively distinguished between cheese types and ripeness stages, achieving high accuracy (up to 0.991 F-measure) using EfficientNet and DarkNet-53 features [257].In conclusion, AI is transforming cheese quality assessment by providing non-invasive, accurate, and efficient methods to predict quality, optimize production, and ensure better control over the cheese-making process [258]. As AI technologies advance, their applications in the cheese industry will continue to expand, providing manufacturers with even more sophisticated tools for producing high-quality cheese. Fig. 9 (A - C) briefly describes the application of artificial intelligence in this cheese field.

10. Conclusions

As described in this review, the effects of different techniques on the physicochemical and sensory properties of cheese types are different. Thus, in order to guarantee the cheese's quality and safety while it is being stored, it is necessary for each variety of cheese to undergo a particular preservation process and ensure that the application circumstances are ideal. Among the innovative preservation techniques, HHP has substantial industrial potential. It can be implemented either independently or in conjunction with other preservation technologies to treat a variety of cheeses. New packaging systems attained considerable attention, particularly in order to extend the shelf life and quality control of cheeses. Nevertheless, these systems necessitate additional research to become more widely applicable in cheese industry. Generally, this review showed that the innovative preservation studies increase the shelf life of hard and semi-hard cheeses and boost dairy industry profitability. Consequence, the impact of preservation methods on food chain sustainability and customer preferences should also be considered. The integration of artificial intelligence into cheese quality assessment and production represents a significant advancement for the industry. By harnessing machine learning, computer vision, and other innovative AI technologies, cheese manufacturers can achieve unprecedented levels of accuracy, efficiency, and consistency in both quality evaluation and production processes. The ability to non-invasively monitor key parameters such as ripeness, texture, and chemical composition not only enhances product quality but also reduces waste and optimizes storage conditions. As these technologies continue to evolve, we can anticipate even more refined tools that will support manufacturers in meeting the growing demand for high-quality cheese while maintaining sustainability. The ongoing development and application of AI will undoubtedly shape the future of cheese production, enabling a more precise and informed approach to this industry.

CRediT authorship contribution statement

Mohammed A. Falih: Writing – review & editing, Writing – original draft, Conceptualization. **Ammar B. Altemimi:** Writing – review & editing, Writing – original draft, Conceptualization. **Qausar Hamed Alkaisy:** Writing – review & editing, Writing – original draft, Conceptualization. **Farhang H. Awlqadr:** Writing – review & editing, Writing – original draft, Conceptualization. **Tarek Gamal Abedelmaksoud:** Writing – review & editing, Writing – original draft, Conceptualization. **Sajed Amjadi:** Writing – review & editing, Writing – original draft, Conceptualization. **Mohamad Ali Hesarinejad:** Writing – review & editing, Writing – original draft, Conceptualization.

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