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Review

A Global Review of Cheese Colour: Microbial Discolouration and Innovation Opportunities

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Abstract: Cheese is a biologically active food product, characterised by its colour, texture, and taste. Due to its rich matrix of fats and proteins, as well as the fact that the cheese's surface acts as its own packaging, the cheese becomes more susceptible to contamination by microorganisms during the ripening process, particularly bacteria and fungi. The ripening of cheese involves several biochemical reactions, with the proteolytic activity of the cheese microbiota being particularly significant. Proteolysis results in the presence of free amino acids, which are precursors to various metabolic mechanisms that can cause discolouration (blue, pink, and brown) on the cheese rind. Surface defects in cheese have been documented in the literature for many years. Sporadic inconsistencies in cheese appearance can lead to product degradation and economic losses for producers. Over the past few decades, various defects have been reported in different types of cheese worldwide. This issue also presents opportunities for innovation and development in edible and bioactive coatings to prevent the appearance of colour defects. Therefore, this review provides a comprehensive analysis of cheese colour globally, identifying defects caused by microorganisms. It also explores strategies and innovation opportunities in the cheese industry to enhance the value of the final product.

Keywords: *Pseudomonas* spp.; *Serratia marcescens*; *Yarrowia lipolytica*; melanin; prodigiosin; edible films

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1. Introduction

Cheese is a food that has been produced for centuries as a method of preserving milk. It is widely consumed due to its flavour and versatility. Across the globe, there is a vast variety of cheeses, each differing in flavour and shape, depending on the cultural traditions and available resources of each region. In 2022, global cheese production reached approximately 22.17 million metric tons. The European Union was by far the largest producer of cheese worldwide, with a production volume of around 10.55 million metric tons that year [1].

Colour is one of the primary attributes that consumers notice in cheese and significantly influences their purchasing decisions. It also serves as an indicator of quality, often correlating with factors like flavour, hygiene, and ripeness [2]. Most cheeses have a natural buttery yellow colour, derived from the β-carotene present in cow's milk. This β-carotene, absorbed by the animal's fat stores, is stored within the milk's fat globules. Due to proteins and fat globule membranes, the yellow pigment is masked, causing milk to appear white. However, during cheese-making, proteins are broken down, and the membranes dissolve due to acidification and rennet, making the yellow hue of β-carotene visible [3,4]. Consequently, cheeses with higher fat content tend to have a richer yellow colour.

In contrast, cheeses made from goat and sheep milk are white because these animals convert β-carotene from their diet into vitamin A (retinol) [4], which is colourless. Thus, goat and sheep milk contain retinol and xanthophylls instead. Seasonal changes also affect cheese colour; in autumn and winter, the reduced availability and lower nutrient value of grass lead to lower β-carotene levels, resulting in cheeses with a paler colour than those made in spring and summer [5].

Many varieties of cheese exhibit a range of colours, particularly shades of orange, white, blue, and yellow. The colour of the cheese is primarily determined by the hue of its rind or surface [6]. The diverse colour variations found in cheeses are attributable not only to intrinsic factors, but also to the addition of colourants that enhance the visual appeal of the product. This possibility makes the use of colourings and/or pigments an area of innovation and development of new products. However, in the case of Protected Designation of Origin (PDO) cheeses, as they are subject to specific product specifications, this type of innovation does not apply. For instance, orange cheeses, such as red Cheddar, Gouda, Prato, and Mimolette, derive their vibrant appearance from the addition of annatto dye as a food colourant during the initial stages of the cheese-making process [6].

Cheese is regarded as a bio-complex ecosystem inhabited by a diverse array of microorganisms, collectively known as cheese microbiota, which originate from raw milk, starter cultures, and adjunct cultures [7]. These microorganisms play a crucial role in contributing to the sensory attributes of different cheeses through their complex interactions with milk proteins, carbohydrates, and fats. This interplay occurs primarily during a key technological process in cheese making known as ripening [8].

Cheese ripening is a complex phenomenon that involves several biochemical reactions [9]. Among these, proteolysis is the most significant multi-step biochemical process during cheese ripening [10]. It is responsible for the development of various organoleptic characteristics, including both flavour and texture [11]. High levels of proteolysis lead to an increased concentration of free amino acids, which have been identified as a substrate for colour defects in cheese. For several years, cases of colour defects on cheese surfaces have been documented in the literature. Sporadic inconsistencies in the appearance of cheese can result in downgrading, leading to economic losses for producers [12–14]. The surfaces of cheeses are particularly susceptible to contamination by microorganisms due to their high water activity and favourable acidity conditions [15]. One of the most effective strategies to prolong cheese shelf life and enhance its quality is proper packaging [15]. Many recently published studies have focused on cheese safety and extending its shelf life.

Edible coatings, which incorporate antimicrobials onto the surfaces of cheeses, are attracting significant attention due to their high levels of active ingredients in the targeted areas [16–18]. Edible coatings have been employed for several years to prolong the shelf life of cheeses. These coatings are primarily made from edible biopolymers and food-grade additives. The film-forming agents can include polysaccharides (such as carbohydrates or gums), proteins, lipids, or a combination of these materials.

Plasticisers such as glycerin, propylene glycol, sorbitol, sucrose, polyethylene glycol, corn syrup, and water can also be added to modify the physical properties and enhance the functionality of the edible films [19]. Additionally, other ingredients, including antioxidants, antimicrobials, nutrients, nutraceuticals, pharmaceuticals, flavours, and colours, have been utilised as functional additives to further extend the shelf life of cheeses [15].

The objective of this review was to conduct a comprehensive assessment of the occurrence of colour defects in cheeses. This review aimed to address two key questions: the origin of the distinct colour defects observed on cheese rinds, and the strategies that producers can employ to prevent and/or mitigate these defects, thereby enhancing colour quality and adding value to the product.

2. Microbial Colour Defects in Cheese

While the safety aspects of smear-ripened cheeses have been extensively discussed in detail by previous reviews [20–24], this review also focuses on the impact of the surface-smear microbiota on the quality aspects of smear-ripened cheeses, which are of utmost importance to the cheese industry. Colour is a visual perception caused by the interaction of light with the surface of an object, resulting from the way light is absorbed, reflected, or transmitted by that object. In the context of cheese, colour can be influenced by various factors, such as the composition of the milk, the manufacturing process, the presence of microorganisms, and the stage of maturation. These factors impact the perception of the product's quality, making colour one of the most influential attributes for the consumer. Defects in cheese smear can result in product recall costs, halt entire production processes, and consequently have a significant economic impact on the cheese industry [21]. Anomalous colour defects affecting different cheese varieties made from raw or pasteurised milk have been reported in various countries (Table 1).

Table 1. Microbial colour defects in several types of cheese.

Colour Defect	Cheese Type	Microorganism	Reference
Brown-violet	Brie	*Pseudomonas* spp.	[25]
Brown	Emmental, Tilsit, Provolone, Grana, Romano, and Parmesan	*Pseudomonas* spp.	[26]
Rusty-brown	Cottage	*Rahnella aquatilis*	[27]
Brown	Gorgonzola	*Candida catemulata* *Candida lipolytica*	[28]
Pink-brown	Brie-type, Camembert-type	*Lactococcus lactis* subsp. *lactis* biovar *diacetylactis*	[29]
Brown	Ewes' milk (raw)	*Yarrowia lipolytica*	[12]
Brown	Pecorino Crotonese	*Yarrowia lipolytica*	[9]
Brown	Goat's milk (raw)	*Pseudomonas putida*	[14]
Pink	Continental-type	*Thermus thermophilus*	[30]
Slight greenish	Ewes' milk (pasteurised)	*Clostridium tyrobutyricum*	[31]
Pink	Gouda	Nitrate-reducing bacteria	[32]
Pink	Grana	*Lactobacillus helveticus*	[33]
Orange	Mozzarella	*Pseudomonas aureofaciens Pseudomonas putida* biovar II	[34]
Orange-red	Mozzarella	*Plantibacter flavus* *Plantibacter agrosticola*	[34]
Orange-red-brown	Mozzarella	*Pantoea agglomerans* *Pseudomonas gessardii*	[34]
Greenish	Mozzarella	*Pseudomonas fluorescens*	[34]
Fluorescent	Mozzarella	*Pseudomonas fluorescens Pseudomonas putida*	[34]
Yellow-brown	Mozzarella	*Phoma glomerata*	[35]
Pink	New Zealand Cheddar	*Streptococcus thermophilus*	[36]
Pink	Romano	*Lactobacillus helveticus* *L. delbrueckii* subsp. *bulgaricus*	[37]
Red	Ricotta	*Serratia marcescens*	[38]
Pink	*Swiss-type*	*Propionibacterium shermanii*	[39]
Blue	*Fresh cheese*	*Pseudomonas fluorescens*	[40]
Red	*Cabrales cheese*	*Serratia marcescens*	[41]

2.1. Blue Colour Defect

The occurrence of the blue defect in various fresh cheese types has been on the rise globally, causing concern among both cheese producers and consumers, even though no pathogenic bacteria are present in the affected products [35]. In recent years, several similar incidents have been reported across Europe and the USA. However, defects in fresh cheeses and other dairy products due to microbial activity are not an uncommon phenomenon [13,42].

In June 2010, Italian national health authorities notified the Rapid Alert System for Food and Feed (RASFF) about altered organoleptic properties—specifically, a blue discolouration—in Mozzarella cheese imported from Germany, along with elevated levels (5.1×10^6 CFU/g) of *Pseudomonas fluorescens*. The following month, reports emerged of "blue Mozzarella" produced within Italy [43]. This issue raised significant concerns across the European dairy industry, leading to the recall of approximately 70,000 Mozzarella balls from the market. The blue defect also impacted certain batches of fresh whey cheeses, and investigations revealed that the contamination originated from the processing water used [44]. Shortly afterward, the blue defect was also observed in Latin-style low-acid fresh cheeses (Queso Fresco) produced in New York State (USA) using pasteurised milk. In this case, an acidulant was added rather than lactic cultures, resulting in a final pH close to 6.0. The defect persisted for nine months, suggesting the presence of a potential permanent reservoir for the causative microorganism [45].

In 2014, fresh cheeses produced in Gran Canaria (Spain) using a blend of raw cow and goat milk, without starter cultures, occasionally showed blue discolouration on the surface. This defect continued to appear even after switching from raw to pasteurised milk in production. Effective elimination of this spoilage required rigorous cleaning and disinfection protocols [46].

Similarly, in 2016, batches of Burgos cheese—a fresh cheese made from pasteurised milk without starter cultures—were seized in Madrid, Spain, due to a purplish-blue defect that appeared upon opening the packaging. Investigations aimed at isolating and identifying microorganisms in the affected cheeses confirmed the presence of the blue defect [40]. In experimental inoculation studies, the causative agent was consistently identified as *Pseudomonas fluorescens*. Furthermore, certain *P. fluorescens* strains were found to produce pyocyanin, the primary pigment of *Pseudomonas aeruginosa*, which contributed to the discolouration.

Pyocyanin is a blue phenazine compound with key roles in iron metabolism, along with notable antibacterial and antifungal properties [47]. It is considered a virulence factor and acts as a quorum-sensing signaling molecule. Pyocyanin has been suggested as the cause of the blue defect in certain cheeses, where *Pseudomonas fluorescens* biovar IV strains were isolated. These strains were found to produce both pyoverdine, responsible for fluorescence, and pyocyanin, which imparts the blue discolouration observed in the defective cheeses [46].

2.2. Pink Colour Defect

The pink defect is a global issue impacting the cheese industry and has been observed in various cheese varieties, including Swiss, Cheddar, Grana, and Italian types [37,39], as well as in ripened cheeses coloured with annatto [48–50]. This defect may present as a band beneath the cheese surface or may be sporadically distributed throughout the cheese. Numerous factors, including physical, biochemical, and microbial influences, have been suggested as contributors to this defect [13]. In some documented cases, the cheese defect was not directly caused by microbial pigment production, but rather by chemical reactions occurring on substrates previously generated through microbial activity. The pink defect in Romano cheese was investigated using starter bacteria such as *Lactobacillus bulgaricus* ATCC 12278 and *Lactobacillus helveticus* ATCC 10797, which create a higher oxidation–reduction potential, and were associated with the defect [51]. Additionally, it has been proposed that compounds like tyrosine, ascorbic acid, pyruvate, and fumarate can accelerate the pink defect in cheese curd when these starters are present [37]. Grana cheese, which is more prone to pinking, exhibited high levels of free amino acids and an abundance of tyrosine crystals, particularly when produced using a specific strain of *Lactobacillus helveticus* as a starter [33].

In New Zealand, the accumulation of galactose in Cheddar cheese manufactured with a starter culture containing Streptococcus thermophilus led to the development of pink colouration [36]. The involvement of non-starter bacteria has also been noted. For instance, the red defect in fresh Ricotta cheese was associated with the presence of Serratia marcescens, likely originating from the milk of cows with subclinical mastitis [39]. The pink defect in ripe Continental-type cheeses has been traced to the carotenoid-producing bacterium *Thermus thermophilus*, which was consistently isolated from hot water samples at the associated dairy plant [30].

Research by Lourenço et al. (2020) demonstrated that the intensity of the pink colour is directly related to the microbial load of *Serratia marcescens* present in the cheese; higher initial microbial loads corresponded to the development of more intense colours [52]. Additionally, a red colour defect in Cabrales cheese, a traditional, blue-veined Spanish cheese made from raw milk, occurs infrequently but can significantly impact family-owned artisanal cheesemaking businesses. This study identified *Serratia marcescens* as the microbe responsible for the appearance of red spots on the surface and adjacent inner areas of such cheese [41]. Jonnala et al. (2021) concluded that the presence of certain Thermus strains in cheese is linked to the development of redness [53]. Higher levels of redness were observed in cheese containing the strain *Thermus thermophilus* HB27, potentially due to carotenoid production by this strain. Although other strains used in the study could also produce carotenoids, they did not result in significantly higher redness. The synthesis of carotenoids by Thermus bacteria requires additional factors, such as light, vitamin B12, glutamate, or oxaloacetate [53].

2.3. Brown Colour Defect

The appearance of various coloured stains on the cheese rind during the maturation process and throughout the marketing period has been a significant issue for producers, particularly in the Beira Baixa region of Portugal. This problem warrants greater attention to develop strategic measures aimed at combating and mitigating its impact. Such issues have also been observed in other countries across Europe and the United States [40], resulting in decreased sales and economic losses.

The brown or brownish colour defect is the most frequently reported issue on cheese rinds. Several studies documenting brown defects in various cheese varieties made from either raw or pasteurised milk have been compiled in Table 2.

Table 2. Microbial identification of browning-type defects in cheeses.

Defect	Cheese Type	Microorganism	Reference
Brown-violet	Brie	*Pseudomonas* spp.	[25]
Brown	Emmental, Tilsit, Provolone, Grana, Romano, and Parmesan	*Pseudomonas* spp.	[26]
Rusty-brown	Cottage	*Rahnella aquatilis*	[27]
Brown	Gorgonzola	*Candida catemulata Candida lipolytica*	[28]
Pink-brown	Brie-type, Camembert-type	*Lactococcus lactis* subsp. lactis biovar diacetylactis	[29]
Brown	Ewes' milk (raw)	*Yarrowia lipolytica*	[12]
Orange-red-brown	Mozzarella	*Pantoea agglomerans* *Pseudomonas gessardii*	[34]
Brown	Pecorino Crotonese	*Yarrowia lipolytica*	[9]
Brown	Goat's milk (raw	*Pseudomonas putida*	[14]

The rusty-brown defect has been observed in Cottage cheese contaminated with *Rahnella aquatilis* when glucono-δ-lactone was used for acidification, but this defect did not occur when lactic or citric acid was used for the same purpose [27]. Similarly, a yellow-brown defect in Mozzarella cheese was linked to the presence of the mould *Phoma glomerata*, with contamination levels ranging from 1.1×10^3 to 4.5×10^4 CFU/g [35]. The orange defect in Mozzarella cheese was attributed to *Pseudomonas aureofaciens* and *Pseudomonas putida* biovar II, while the orange-red defect was associated with *Plantibacter flavus* and *Plantibacter agrosticola*. Additionally, the orange-red-brown defect was linked to *Plantibacter brassicacearum*, and the yellow-purple defect was related to *Pantoea agglomerans* and *Pseudomonas gessardii* [34].

Pseudomonas spp. has also been implicated in the brown defect of Portuguese cheese rind made from raw milk and cheese agar medium [54]. The brown surface defect in ewes' raw milk Portuguese cheese has been connected to tyrosine metabolism by the yeast

Yarrowia lipolytica [12]. Another study suggested that the enzymatic conversion of tyrosine into melanin pigments, driven by the action of tyrosinase, could result in a brown defect on cheese rind [14,55]. Ferraz et al. (2021) reported that eumelanin is the pigment produced by *Pseudomonas putida* ESACB 191, which was isolated from the brown rind of cheese [14]. The production of melanin by *P. putida* ESACB 191 is dependent on the concentration of tyrosine in the culture media [14].

The most common pathways for melanin synthesis in bacteria involve melanin precursors derived from tyrosine transformations [14]. This monohydroxylated compound is oxidised to produce dihydroxylated (diphenol) derivatives through reactions that preserve the amino group. DOPA melanins are synthesised by tyrosinases [55,56].

Tyrosinases (EC 1.14.18.1) are bifunctional copper-containing polyphenol oxidases that catalyse the hydroxylation of tyrosine to L-DOPA, followed by its oxidation to o-dopaquinone [57]. This quinone undergoes spontaneous cyclisation to form indole quinone, which ultimately leads to the spontaneous polymerisation of this compound or its carboxylate form, resulting in the formation of brown to black DOPA melanins, also referred to as eumelanin [58].

Bacteria belonging to the genus Pseudomonas are ubiquitous microorganisms that are widely distributed in the environment and possess high metabolic versatility. This genus includes plant pathogens, opportunistic pathogens affecting humans and animals, as well as organisms responsible for food spoilage [42]. Their ability to grow at refrigeration temperatures, along with their robust proteolytic and lipolytic systems and production of undesirable volatile compounds [59–62] significantly contribute to their spoilage potential in milk and dairy products [46]. Additionally, Pseudomonas species can synthesise brown pigments such as eumelanin, pyomelanin, pyocyanin, pyoverdine, and pyorrubin, which can cause defects in cheeses and other food products.

3. Strategies to Mitigate Colour Defects in Cheese

The colour of cheese holds significant importance for consumers, as they associate specific characteristics such as quality, flavour, and maturity with colours [5]. Numerous food colourant industries produce a diverse range of natural colour preparations for use in the food, pharmaceutical, and cosmetics sectors. Natural colours include annatto, saffron, paprika, beetroot red, β-carotene, turmeric, caramel, carmine, elderberry, anthocyanin, and various natural green extracts.

Next, we will delve into the primary natural dyes commonly used in the dairy industry. Within the European Union (EU), colourants permitted for use in cheese production are authorised by the EFSA (European Food Safety Authority). Moreover, the European Parliament and Council Directive 94/36/EC on colours for foodstuffs outlines the approved food colours. For cheese and other dairy products, only specific authorised dyes may be added, with maximum allowable levels specified in the Directive [63] (Table 3).

3.1. Annatto

Annatto, derived from the seeds of the *Bixa orellana* L. plant, is widely used as a food colourant and in cheese production. It is recognised as food additive E 160b (Table 3), approved by the European Union. Commercial annatto extracts are available in stabilized forms and come in a range of colours, from red to orange to yellow, making them suitable for use in various foods, including dairy, fish, confectionery, beverages, meat products, snack foods, and dry mixes [64].

More than 80% of annatto's active compound, bixin, consists of cis-bixin (methyl hydrogen 9′Z-6,6′-apocarotene-6,6′-dioate) [6]. Annatto is responsible for the characteristic colour of orange cheeses, such as red Cheddar, Gouda, Prato, and Mimolette, which are coloured by the addition of annatto dye to the milk at the beginning of the cheese-making process. The shade of cheese can vary from bright yellow to deep orange [6], depending on the region where it is sold. Annatto is also used to colour the milk in the production of Red Leicester, Double Gloucester, red Cheddar, Mimolette, Cheshire, and Prato cheeses.

Table 3. Permitted colourants (Directive 94/36/EC) that may be considered for application in cheese.

Colourant	Cheese
E 160b Annatto, Bixin, norbixin	Red Leicester cheese
E 120 Cochineal, Carminic acid, Carmines E 163 Anthocyanins	Red marbled cheese
E 160b Annatto, Bixin, norbixin	Mimolette cheese
E 160a Carotenes E 160c Paprika extract E 160b Annatto, Bixin, norbixin	Ripened orange, yellow, and broken-white cheese: unflavoured processed cheese
E 153 Vegetable carbon	Morbier cheese
E 140 Chlorophylls, chlorophyllins E 141 Copper complexes of chlorophylls and chlorophyllins	Sage Derby cheese
E 161b Lutein E 140 Caramel II, sulfite caramel E 100 Curcumin	Ripened cheese
E 150d Caramel IV—sulfite ammonia caramel E 120 Carmines E 160a Carotenoids E 160c Paprika extract E 101 Riboflavins	Ripened cheese, including rind

3.2. *Paprika*

Paprika extract, typically a deep red powder with a strong flavour, is made by grinding dried pods of sweet pepper (*Capsicum annuum*). It contains primarily two carotenoids, capsanthin and capsorubin, which provide the characteristic yellow-to-orange colour of paprika [64]. The fat/oil-soluble form of paprika extract, known as oleoresin, is obtained by using hexane as a solvent. Paprika is commonly used as a spice in savory foods, and its use as a colourant is approved by the EFSA under the code E 160c (Table 3). Although there are limited reports on paprika's use in natural cheese, it has been applied to the surface of goat cheeses like Ibores and Majorero, often mixed with olive oil [6]. In Portuguese traditional cheese-making, especially for cheeses made from raw milk from goats and sheep, paprika is used to colour the cheese rind and correct secondary colour defects.

3.3. *β-Carotene*

The pigment *β*-carotene is naturally found in the milk of grass-fed lactating cows and has been successfully used to colour cheese in the past. *β*-carotene is an effective cheese colourant because it is naturally present in milk, provides an appealing colour for consumers, and does not cause off-flavours during the cheese ripening process [6,64].

β-carotene can be chemically synthesised or extracted from natural sources using food-grade solvents. In addition to its use as a colourant, *β*-carotene plays an important role in human health, as it is a precursor to vitamin A and, when consumed with vitamins C and E, may help prevent cardiovascular diseases and cancer [65].

However, adding *β*-carotene to milk or water-based foods can be challenging due to its fat-soluble nature. To address this, *β*-carotene should be added in a pre-emulsified form or incorporated into a portion of the cheese milk followed by homogenization [6]. The production of dairy products, such as cheese and butter, can lead to the transfer of certain constituents, including colourants, from milk to the final products. Since carotenoids like *β*-carotene are fat-soluble, they tend to associate with milk fat, resulting in minimal transfer to the whey [66].

3.4. Lutein

Lutein (3,3′-dihydroxy-α-carotene) is a natural yellow-red-coloured fat-soluble pigment with antioxidant properties, found in green leafy vegetables and yellow carrots [67]. Regular intake of lutein helps to prevent age-related macular degeneration disease [68]. Lutein is a xanthophyll, a carotenoid that has been effectively used as a food colourant in a wide variety of products, including sauces, seasonings, soups, certain alcoholic beverages, marmalades, flavoured drinks, jams, jellies, cheese rinds and processed cheese, flavoured dairy products, edible cheese rinds, edible ices, desserts, confectionery (such as breath fresheners and chewing gum), pastries, fine bakery goods, appetizers, sauces, fish paste, and crustacean paste [69]. In a study by Sobral et al. (2016), annatto (bixin) was successfully replaced with lutein in Prato cheese without compromising its sensory quality or consumer acceptance [68].

3.5. Saffron

Saffron, a spice obtained from the stigmas of *Crocus sativus* L. flowers, is sometimes used as a natural colourant in cheese [70]. Known for its distinctive bitter flavour, due to the compound picrocrocin, and its aroma primarily from safranal, saffron is valued for its vivid colour, provided by water-soluble carotenoids called crocetin esters [70]. When used as a colourant, saffron falls under the category of “colouring foods” rather than regulated food additives, thus exempt from additive regulations. One well-known cheese featuring saffron is Piacentinu Enesse, a hard cheese made from sheep’s milk, where saffron enhances both the colour and the flavour.

Adding saffron to milk is more complex than to water, as milk contains fat emulsions and colloidal casein suspensions, and its composition varies based on factors like breed, diet, milking method, and lactation phase. For instance, higher fat content in milk results in a more intense yellow hue in saffron-coloured cheeses. The water-soluble compounds in saffron, like crocetin esters, interact with milk’s hydrophilic and amphiphilic elements in the serum phase, such as whey proteins, milk fat globule membrane (MFGM) proteins, and phospholipids [71]. Further research is needed to clarify how these interactions affect saffron’s behavior in milk.

Studies by Licón et al. (2012) show that adding saffron to milk reduces salt absorption in cheese, making it more deformable and less elastic than non-saffron cheeses, without affecting composition, microbiology, or general sensory qualities [71]. Saffron-coloured cheeses tend to be less bright, less red, and more yellow than control samples, with significantly higher b* (blue-yellow) chromaticity values, similar to those seen in Cheddar cheeses coloured with annatto [6]. In saffron cheeses, lower a* (green-red) values and higher L* (lightness) values were observed, creating a more intense yellow tone [72].

In sensory evaluations, saffron cheeses were distinguished by flavour differences from non-saffron varieties. Research on fresh sheep cheese with saffron stored at 4 °C for 30 days found that saffron did not impact total aerobic bacteria or *Lactococcus* cultures, but did exhibit antimicrobial effects against coliforms and enterococci. Additionally, saffron provided antioxidant benefits. The primary changes observed were in colour and taste, with the cheese becoming more yellow as saffron concentration increased. A cheese made with 50 mg/L saffron was particularly well-received, delivering a traditional taste profile appreciated by Greek consumers [73].

4. Strategies to Prevent Colour Defects in Cheese

To prevent microbiological defects, it is crucial to adhere to good manufacturing practices and maintain hygiene standards from milking through to shipping, particularly for raw milk cheeses. This area also presents promising opportunities for the development of active packaging that can manage microorganisms throughout the cheese’s shelf life.

A significant source of loss in cheese commercialization occurs during storage, where contamination by bacteria, moulds, and yeasts is frequent. This contamination can cause colour irregularities and off-flavours, lowering the cheese’s quality, especially when stored unpackaged. Additionally, certain cheese types face issues from excessive moisture loss, which can increase hardness and lead to undesirable sensory qualities. To combat these problems, various packaging solutions have been developed, including vacuum packaging and modified atmosphere packaging, both applied to different cheese varieties. Common materials used in these packaging systems include polyethylene, polyamide, and polypropylene [74].

Coatings are also widely used to preserve and package cheese, either as standalone protective layers or as supplementary barriers alongside other packaging methods. Traditionally, coatings have been made from petroleum-based materials, such as paraffin wax and polyvinyl chloride. However, due to environmental and sustainability considerations, as well as regulatory limits, the use of edible films and coating materials is becoming increasingly popular. These edible coatings offer an eco-friendly alternative that, like traditional coatings, helps prevent spoilage, extend shelf life, and minimise moisture loss. Numerous studies have investigated the effects of edible films and coatings on different types of cheese, highlighting their potential benefits [17,75–79]. Edible films and coatings can serve as carriers for antimicrobial agents, providing distinct advantages over traditional coatings, such as improved spreadability, diffusivity, and solubility [80]. Using active coatings is an effective method to prevent colour defects in cheese during storage, while also extending its shelf life.

Cheeses can be produced using various types of milk and processing techniques, ripened for different durations, leading to a multitude of varieties with significant diversity in texture, flavour, and shape. Hard, semi-hard, and soft cheeses are nutrient-dense dairy products with versatility in culinary applications. However, the development of off-flavours can diminish cheese quality, particularly when stored without packaging. Additionally, excessive moisture loss in certain cheese types can increase hardness and result in undesirable organoleptic properties. The primary economic losses within the cheese industry often occur during the ripening and storage phases, where cheese is susceptible to contamination by bacteria, moulds, and yeasts. Extending the shelf life of dairy products has always been a priority for the industry. Traditionally, preservation methods included leveraging natural atmospheric conditions—such as sun-drying in summer and cold storage in winter—alongside natural fermentation to help preserve cheese [81].

More recently, active and intelligent packaging solutions, as well as non-thermal technologies, have emerged to reduce spoilage in perishable foods. In response to these challenges, there is growing interest in packaging made from edible biopolymers, including proteins, polysaccharides, and lipids sourced from renewable materials or industrial by-products. These biopolymer-based materials are fully biodegradable and eco-friendly, offering a sustainable alternative to the petroleum-based packaging widely used in the food sector.

The terms "coatings" and "films" are often used interchangeably; however, the primary distinction lies in their thickness. Films are thin layers of polymers that are initially molded as solid sheets and utilised for wrapping products, whereas coatings are directly applied to the product's surface, typically through immersion in a polymer solution [81]. Consequently, coatings are generally thinner than films and remain on the product during use and consumption. Edible films and coatings can be ingested alongside the food product, effectively serving both as food and as packaging [82]. The main objective of edible films and coatings is to enhance the quality, safety, and shelf life of food items [83].

4.1. Natural Biopolymers

Biopolymers, including polysaccharides, proteins, and lipids, can be employed to create edible films and coatings for cheese, incorporating antifungal agents encapsulated within the polymer matrix. This encapsulation is designed to minimise the migration of the antifungal compounds within the cheese, enhancing their efficacy on the cheese surface [84].

Biopolymers offer numerous advantages, such as biodegradability, recyclability, and sustainability; however, they do come with certain limitations, notably their inadequate mechanical and barrier properties [85]. To develop highly effective coatings, the solutions are synthesised and dried under controlled temperature and relative humidity conditions. Additionally, adjustments to the pH or heating of the solutions may be necessary to facilitate the dispersion of the polymers.

4.1.1. Polysaccharide-Based Coatings

The primary polysaccharide components commonly used for edible coatings include starch, chitosan, pullulan, alginate, carrageenan, modified cellulose, pectin, gellan gum, and xanthan gum, among others. These polysaccharides possess several beneficial properties, including biodegradability, non-toxicity, antibacterial and biocompatibility, transparency, antifungal activity, and good mechanical strength. Additionally, they exhibit high water vapour permeability and serve as barriers to gases, often being blended with other polymers for enhanced performance [86,87].

Starch and alginate are the most frequently used biopolymers in the production of edible films and coatings. Starch is regarded as the universal biopolymer for bio-packaging and has been employed for decades due to its favourable characteristics and gelatinisation properties. Alginate, another significant biopolymer, is known for its ability to form hydrogels and encapsulation barriers [88].

Chitosan is a natural polysaccharide composed of a linear chain of (1–4) linked 2-amino-2-deoxy-D-glucan. It is chemically derived from chitin through alkaline treatment at elevated temperatures. Chitosan is widely found in nature and exhibits antibacterial effects [89].

Since polysaccharides are inherently hydrophilic, their structural integrity can be compromised in highly humid conditions. This hydrophilicity can be mitigated by incorporating lipophilic substances, such as waxes and oils. Furthermore, the addition of antimicrobial agents and antioxidants to packaging materials may help slow down the ripening process of food products and enhance their shelf life [90].

4.1.2. Lipid-Based Coatings

Fats and oils can create a thin, sealable layer on the surface of food, forming a barrier between the food and its external environment. Lipid compounds used as edible polymers include acetylated mono-glycerides, paraffin wax, beeswax, and various surfactants [91]. The primary function of lipid-based coatings is to inhibit moisture transfer due to their relatively low polarity. These coatings are noted for their excellent moisture barrier properties during handling and serving, although they typically yield surfaces with lower elasticity. Lipid coatings also tend to have a shiny appearance and reduce moisture loss. The primary components of these materials are derived from plant and animal fats, while essential oils also fall under the lipid category.

These lipids are hydrophobic, and many possess antibacterial properties, thanks to the presence of terpenoids and terpenes [92]. Essential oils comprise a complex mixture of both volatile and non-volatile constituents, and their composition can vary significantly. For instance, oregano essential oil has been previously utilised to inhibit microbial growth in food products. Its active component, carvacrol, is known for its strong antifungal properties and its high inhibitory effects against pathogens such as *Listeria monocytogenes*, *Salmonella*, *Escherichia coli*, and *Staphylococcus aureus* [93].

Additionally, the essential oil of *Pimpinella saxifraga*, recognised as a novel natural bioactive compound, has been effectively incorporated into sodium alginate coatings for cheese preservation. This essential oil is predominantly composed of anethole, which demonstrates potent antioxidant and antibacterial properties [94].

4.1.3. Protein-Based Coatings

Edible packaging proteins are primarily derived from animal sources, such as gelatin, casein, whey proteins, collagen, and egg albumin. However, plant-based proteins, including corn, soybean, wheat, cottonseed, peanut, and rice proteins, are also valued and compatible with vegetarian diets [91]. The most commonly used proteins for the creation of functionalised (edible) films and coatings include casein, gelatin, wheat gluten, soy protein, and zein.

From an industrial perspective, protein-based food packaging is particularly advantageous due to its biodegradability, affordability, and sustainability [95]. Many proteins have been effectively utilised as coating agents because they create effective barriers against oxygen (O_2) and carbon dioxide (CO_2) permeability. Each type of protein possesses a unique set of physicochemical properties; the specific sequence of amino acids allows for a diverse range of both intra- and intermolecular interactions, as well as interactions with other materials involved in forming the edible matrix [96].

Proteins can be classified as either fibrous or globular. Globular proteins are folded into compact shapes, while fibrous proteins are structured in parallel strands. While protein-based coatings are inherently hydrophilic and do not offer significant resistance to water vapour, they do possess commendable organoleptic and mechanical properties [87].

Milk proteins, particularly casein and whey proteins, are highly valued in the production of edible films and coatings due to their significant physical properties, including water solubility and emulsifying ability, alongside their nutritional benefits [97]. The surplus availability of whey proteins has generated considerable interest within the packaging industry, as they can be used effectively as films or coatings to protect food surfaces from degradation caused by chemicals or microorganisms. This application contributes to extending the shelf life of food products and maintaining high quality [98].

Whey protein films exhibit superior mechanical and barrier properties compared to polysaccharide-based and other protein-source films, making them an attractive option for food preservation [97]. Key features of whey protein coatings include their appealing appearance, inherent biodegradability, appropriate mechanical barrier and optical properties, and the ability to incorporate functional compounds. However, they do face limitations regarding moisture barriers and certain mechanical properties [98].

To enhance the desired characteristics of whey protein films, techniques such as cross-linking through physical, chemical, or enzymatic methods, as well as blending with plasticisers, can be employed [80]. Numerous studies have been conducted to evaluate the effectiveness of edible films and coatings on various types of cheese [17,75,77,99]. These edible films can also incorporate antimicrobial agents, providing advantages over conventional coatings, such as improved diffusion, diffusivity, and solubility [100]. For instance, Ferraz et al. (2023) studied a bioactive edible film based on whey protein isolate, demonstrating its efficacy in preventing brown defects on cheese rind while significantly extending the cheese's shelf life [18].

4.2. Synthetic Polymers

Conventional coating materials, primarily derived from petroleum products like paraffin wax and polyvinyl chloride (PVC), have been widely used in the food industry. However, growing environmental concerns and sustainability issues, coupled with legislative restrictions, have led to an increased focus on edible films and coatings. These materials not only help prevent spoilage and extend shelf life, but also reduce water loss, making them a promising alternative to traditional coatings [101]. Synthetic polymers used for coatings include Polyvinyl Alcohol (PVA), known for its transparent and flexible films [101], and Polyethylene Glycol (PEG), which offers excellent mechanical properties for food packaging [102]. Polyvinyl Pyrrolidone (PVP) is water-soluble and creates clear films, ideal for certain food coatings. Synthetic polyesters, like Poly Lactic Acid (PLA) and Polyhydroxybutyrate (PHB), are used for their film-forming capabilities and good barrier properties, making them suitable for food product applications [103].

As consumer awareness grows regarding the negative environmental and health impacts associated with conventional packaging, there is an increasing demand for biodegradable and sustainable options. This shift reflects a broader trend toward eco-friendly packaging solutions that align with consumer values and preferences.

5. Applications of Edible Coating for Different Types of Cheese

Edible coatings for cheese offer a range of advantages. They help reduce moisture loss, which is essential for retaining the cheese's natural hydration and preventing it from drying out. Additionally, these coatings create a barrier against microbial contamination, enhancing safety, extending shelf life, and reducing the risk of colour or spot defects on the cheese rind. Edible coatings also improve appearance by providing either a glossy or matte finish, making the cheese more visually appealing. They can regulate moisture migration, helping to maintain optimal texture and preventing issues like surface cracking or excessive hardness.

Ongoing research and development in edible coatings for cheese aim to advance coating materials, application methods, and functionality. Scientists are exploring ways to incorporate antimicrobial compounds or natural extracts into coatings to boost safety and quality. There is also interest in developing coatings that enable the controlled release of flavours or additives, enhancing consumers' taste experience. With continued research and technological progress, edible coatings have the potential to significantly impact the cheese industry, offering higher quality products with extended freshness and improved sustainability.

Table 4 show the last 4 years of edible coating and film innovations for different types of cheese.

Table 4. Edible coating and film innovations for different types of cheese in the last 4 years.

Cheese Type		Edible Coating Materials	Functional Properties	Reference
Soft Cheese	Fresh cheese	Whey protein concentrate (WPC)/Rosemary + Sage	Protect the soft cheese from spoilage or pathogenic bacteria	[104]
		Alginate/Bacteriocin-producing *Lactococcus* strains	Protective antimicrobial barrier by reducing bacterial contamination after processing	[105]
	Ultra-filtered cheese	Chitosan/Sodium alginate/CMC	Improve the shelf life, decrease the loss in moisture content	[106]
	Acid curd cheese	Sodium alginate/CMC/wild garlic extract	Prolong the shelf life of cheese	[107]
	Panela cheese	sodium caseinate/chitosan mesoporous silica/oregano essential oil	Good antimicrobial activities and increase the shelf life of soft cheese	[37]
	Fresh curd cheese	Liquid whey protein concentrate/Cinnamon extract	Extend the shelf life of perishable fresh curd cheese, enhance its functional value	[108]
	Ultra-filtrated (UF) cheese	Chitosan/Natamycin	Increased shelf life, enhances the nutritive properties with no negative effects on the quality	[109]
	Double cream	Starch/Microcrystalline cellulose Garlic + oregano oils	Inhibited the growth of pathogenic	[110]
	Karish cheese	Whey protein concentrate/Rosemary oils/Candelilla wax	Prolong the shelf life of cheese enhanced the antimicrobial activity	[106]

Table 4. *Cont.*

Cheese Type		Edible Coating Materials	Functional Properties	Reference
Semi-soft cheese	Mozzarella	Gelatin/Persian gum/Purple car rot extract PCE	Improve the shelf life of mozzarella cheese	[111]
		Natamycin/hydroxyethyl cellulose	Avoid Penicillium Spp. Growth on Low-Moisture cheese	[112]
		Purslane extract/Chitosan	Inhibited the oxidative damage and growth of microorganism during storage at room temperature or in the refrigerator	[113]
		Hydroxypropylmethyl cellulose/Nisin	Good antimicrobial activity, extend the shelf life	[114]
	Beira Baixa goat cheese	WPI, sorbitol, melanin, citric acid, nisin, and natamycin	Improve the antimicrobial activity, extend the shelf life, avoid colour defects	[18]
	Emmental	Sweet whey/Glycerol Sunflower oil/Guar gum	Improve the physicochemical, sensory attributes, and improve the shelf life of Swiss cheese	[115]
	Iranian Lighvan cheese	Alginate-collagen films/betanin/cumin essential oils	Changes and oxidation of lipids, increased the quality	[116]
Hard Cheese	Mongolian	Casein/Chitosan/flaxseed gum	Extend the shelf life of cheese by self-assembly on its surface	[117]
	Ras cheese	Chitosan/Guar gum Roselle calyx extract/ZnO-NPs	Prolong the shelf life and improve the antioxidant and antibacterial properties, reduced weight loss	[118]

6. Commercial Applications and Future Trends

The current market landscape shows a rising interest in edible coatings and films specifically designed for cheese, with several companies actively developing innovative solutions to extend shelf life and improve quality. Notable players include Improveat (Braga, Portugal), a company specialising in bio-based coatings for various food products, including cheese, with a strong focus on sustainability that aligns well with the evolving food industry. Becor Barbanza S.L. (La Coruña, Spain) offers a diverse range of coatings, including edible options for cheeses, reflecting their commitment to quality and innovation in cheese preservation. Vink Chemicals GmbH & Co (Kakenstorf, Germany) also provides a variety of coatings, including natural options for cheese, meeting the growing demand for safe and effective food packaging solutions.

In addition to these companies, the increasing number of patents being filed highlights the commercial potential of edible coatings and films. Successful commercialisation by companies in various countries underscores edible coatings as a viable solution for extending cheese shelf life. As awareness and demand for these sustainable options continue to grow, further research and development may lead to widespread adoption across different cheese varieties.

7. Conclusions

The food industry carries the crucial responsibility of providing consumers with fresh, appealing, and high-quality products that contribute positively to health. Edible coatings, made from safe and consumable ingredients, have emerged as a key solution in food packaging. These coatings offer several benefits, including enhanced product safety by protecting against contaminants and spoilage, reduced packaging weight, which lowers transportation costs, and improved visual appeal to attract consumers. They are cost-effective due to the use of biopolymers, and help extend shelf life by acting as a protective barrier against issues such as weight loss, hardness, discolouration, off-flavours, and microbial spoilage, particularly for semi-hard and soft cheeses.

While many existing studies focus on semi-hard and soft cheeses, there is growing interest in exploring the application of edible coatings across a broader range of cheese types. The goal is to address recent advancements in edible coatings for cheese packaging, highlighting their potential to improve product quality and extend shelf life.

Looking ahead, the industrialisation of edible coatings will require further research to optimise their quality and reduce production costs. This research could unlock the full potential of edible coatings in the dairy industry, making them a viable option for preserving and enhancing the quality of cheese and other perishable food products.

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