RURAL SUSTAINABILITY RESEARCH
53(348), 2025
ISSN – 2256-0939

Received: 24 November 2024 Revised: 7 January 2025 Accepted: 3 April 2025

Biodegradable coatings and packaging solutions for dairy products

***Inga Sarenkova[1,2], Renate Ruska[1], Sanita Sazonova[1], Sergii Verbytskyi[3], Antonina Minorova[3], Sandra Muizniece-Brasava[1]**

[1] Latvia University of Life Sciences and Technologies, Liela street 2, Jelgava, Latvia
[2] Institute of Agricultural Resources and Economics, Zinātnes street 2, Priekuļi, Cēsis Municipality, Latvia
[3] Institute of Food Resources of National Academy of Agrarian Science, Mykhaila Omelianovycha-Pavlenka street 9, Kyiv, Ukraine

Abstract. In recent years, the focus has increasingly shifted towards sustainable packaging solutions, with a rising interest in utilising edible materials for dairy product packaging. The dairy industry has substantial potential for the utilisation of edible coatings and films, as indicated by recent research in this field. The selection of packaging material and design plays a crucial role in ensuring that each packaged dairy product meets expected standards of shelf-life, quality and safety, while also being cost-effective, visually appealing, and environmentally sustainable. Effective packaging can enhance efficiency, minimise waste, and improve overall product quality. This review consolidates recent findings on edible biodegradable packaging applications for cheese, highlighting key advancements, and offering insights into future trends with a focus on environmentally friendly practices within the dairy industry. It also discusses current testing possibilities for biodegradable packaging across various dairy products.

Key words: Cheese packaging, biodegradable material, edible films, sustainability, dairy.

Introduction

In recent years, the application of plastic materials has increased extensively for food product packaging. In 2021, the average amount of plastic packaging waste produced per individual in the EU amounted to 35.9 kg, with approximetly14 kg being recycled. Over the period from 2011 to 2021, there was a significant increase (26.7%) of plastic packaging waste, representing an additional 7.6 kg per person. During the same period, the amount of recycled plastic packaging waste also showed a significant rise of 38.1%, equating to an additional 3.9 kg per person (Eurostat, 2023). A prevailing trend in food packaging is substituting petroleum-based plastic materials with biodegradable and edible alternatives (Jouki *et al.,* 2013; Ahmed *et al.*, 2024). Edible coatings reduce plastic waste and support sustainability objectives, offering a meaningful advantage for the dairy industry as a whole (Jurić *et al.*, 2024). For dairy product manufacturers, the shift towards biodegradable packaging is becoming increasingly essential due to growing environmental concerns, regulatory pressures, and consumer demand for sustainable alternatives. The dairy industry, which relies heavily on plastic packaging for products, such as cheese and yoghurt, is a significant contributor to plastic waste accumulation. Traditional packaging materials not only pose disposal challenges but also jeopardise brand reputation as sustainability expectations rise. By integrating biodegradable and edible coatings, dairy manufacturers can reduce their environmental footprint while maintaining product quality and safety. However, despite the clear advantages, further research is needed to overcome material limitations and regulatory hurdles to ensure widespread adoption of these sustainable solutions (Cammarelle *et al.*, 2021). Cheese packaging plays a critical role in preserving product quality and ensuring consumer satisfaction. Traditional packaging materials, however, often contribute to environmental pollution and pose challenges in terms of disposal and recycling. In response to these concerns, edible biodegradable coatings have emerged as a promising alternative for cheese packaging. These coatings, typically composed

* Corresponding Author's email address: inga.sarenkova@inbox.lv

DOI: 10.2478/plua-2025-0002

of natural materials, offer the potential to mitigate environmental impact while maintaining the integrity of cheese (Rejeesh & Anto, 2023).

Despite increasing interest in this field, the full potential of edible and biodegradable materials for cheese packaging has not yet been fully investigated. While edible biodegradable materials present significant potential for application in cheese packaging, several challenges and limitations hinder their widespread adoption. One significant challenge is the limited understanding of how these edible coatings interact with cheese during storage (Costa *et al.*, 2018). Factors, such as moisture migration, gas exchange, and microbial activity, can influence the safety and quality of cheese; however, the effects of edible coatings on these parameters remain poorly understood (Han *et al.,* 2018). Additionally, the mechanical properties of edible coatings may not always fulfil the requirements for effective packaging, potentially resulting in issues, such as brittleness or inadequate adhesion to the cheese surface. Furthermore, regulatory considerations regarding the use of edible coatings in food packaging must be addressed to ensure compliance with safety standards (Rejeesh & Anto, 2023).

The search for innovative packaging solutions has led to significant advancements in coatings and edible films for cheese packaging. This review has been guided by a combination of scientific exploration and practical research, aiming to improve the sustainability and functionality of dairy product packaging materials. With a focus on current scientific insights, this paper explores the latest developments in edible film coatings specifically for cheese packaging. By examining the multifaceted benefits and challenges associated with these coatings, we aim to expand the perspective on cheese packaging, providing essential viewpoints for researchers, stakeholders and industry experts. Within the second part of the review, current testing approaches for biodegradable packaging options across various dairy products were examined. Recognising that edible film coatings present significant challenges for protecting and preserving the quality of dairy products during storage, this research goes one step closer to developing fully biodegradable packaging solutions tailored to meet the diverse needs of the dairy industry.

Materials and Methods

The monographic method was used for this study. The *first part* of the review summarises the latest findings on edible biodegradable packaging materials for cheese, while the second part discusses the current testing of biodegradable packaging options for various dairy products. The information in this study was primarily sourced from research databases, such as *Web of Science*, *PubMed*, *Scopus,* and *ScienceDirect*. Specific keywords, such as ‘edible coatings’, ‘biodegradable films’, ‘cheese packaging’, ‘dairy product preservation’ and ‘sustainable packaging’ were used to identify relevant publications. Sixty-four scientific articles, reviews and experimental studies were selected based on their relevance, originality, and contribution to the field from 2004 to 2024. These articles encompass a broad geographic scope, with contributions from researchers in Europe, Asia and North America, reflecting a global commitment to advancing sustainable practices in dairy packaging. This diverse dataset ensures a comprehensive review, drawing on international expertise and the latest innovations in biodegradable and edible packaging technologies.

The *second part* of the research was managed in the scientific laboratory and the laboratory of microbiology in the Faculty of Agricultural and Food Technology, Latvia University of Life Science and Technology in Jelgava, Latvia. The following dairy products were selected for the study: 20% sour cream (“Farm Milk Sp. z o.o.”, Poland), semi-hard cheese (“Smiltenes Piens”, Latvia), 3% natural yoghurt (“Farm Milk Sp. z o.o.”, Poland), 9% cottage cheese (“Jaunpils Pienotava”, Latvia) and 82% butter (“Mlekovita”, Poland). The selected dairy products were obtained in local retail markets, with a shelf life exceeding 10 days from the purchase date (30 days for semi-hard cheese). The products were immediately stored at 4 ± 2 °C and subsequently handled one by one under sterile conditions in a laminar flow cabinet, where they were prepackaged using various materials: polylactic acid (PLA) containers (NatureWorks), CERAMIS polylactic acid coated with a silicon oxide layer (Amcor), and polyolefin biodegradable shrink film (PTC). The laboratory air was also sterilised with UV light for 2 hours before the repackaging process to minimise external contamination of the products being repackaged and subsequently directed to the sealing equipment.

The samples were labelled with letters and numbers, where the letters indicated the packaged dairy product, and the numbers represented the packaging material. Sample codes and their descriptions are shown in Table 1.

The samples shown in Figure 1 were stored at 4 ± 2 °C for 10 days (30 days for semi-hard cheese). Number 1 samples are dairy products in original packaging. Sour cream is packaged in a low-density polyethylene pillow-shaped package which provides flexibility and basic protection. 3% natural yoghurt is in a polypropylene cup, chosen for its durability and suitability for acidic products. The semi-hard cheese

Table 1

Sample code description

Sample code	Description
SC	20% sour cream
Y	3% natural yoghurt
HC	semi-hard cheese
CC	9% cottage cheese
B	82% butter
1	Control sample (dairy product in original package). SC in low density polyethylene (LDPE) pillow-shaped package; Y in polypropylene (PP) cup; HC in a multi-layer vacuum cushion-shaped polyethylene/polyamide (PE/PA) package; CC in in a multi-layer thermoformed package; B in a composite material with a metallised layer
2	Polylactic acid coated with a silicon oxide layer
3	Polylactic acid containers
4	Polyolefin biodegradable shrink film

A comparative display of sustainable packaging solutions is shown in Fig. 1.

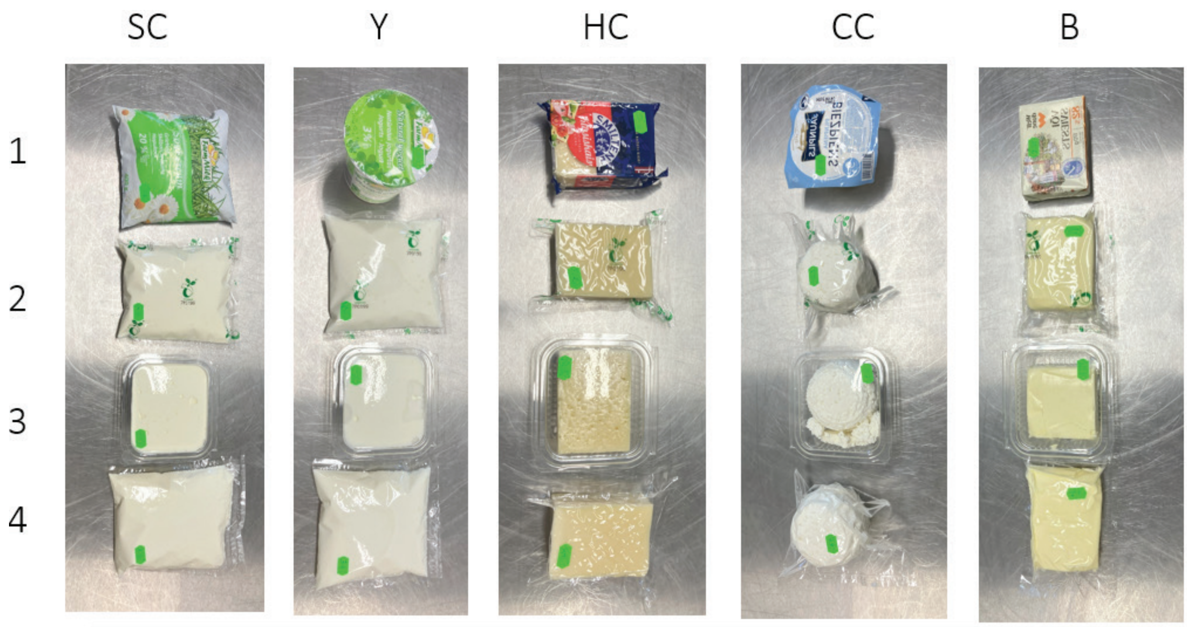

Figure 1. Dairy products SC: 20% sour cream; Y: 3% natural yoghurt; HC: semi-hard cheese; CC: 9% cottage cheese; B: 82% butter, packaged in various biodegradable materials (1: original packaging; 2: polylactic acid coated with silicon oxide layer; 3: polylactic acid containers; 4: polyolefin biodegradable shrink film).

is packaged in a multi-layer vacuum cushion-shaped package made from polyethylene and polyamide, designed to provide a strong oxygen barrier. The 9% cottage cheese is stored in a multi-layer thermoformed package, which offers an effective seal and protection against moisture loss. Finally, the 82% butter is packaged in composite material with a dominant metallised layer, providing essential light and oxygen barriers to prevent spoilage and preserve flavour.

Samples were analysed every two days, while cheese samples were tested every six days. The analyses included pH, moisture content, water activity, and microbiological tests:

- *Microbiological tests.* Samples for microbiological testing were prepared following the standard LVS EN ISO 6887–2:2004 method. The total count of mesophilic aerobic and facultatively anaerobic microorganisms (MAFAm) was determined according to the LVS EN ISO 4833–2013 standard using Plate Count Agar (PCA) at 30 ºC ± 1 ºC for 72 ± 3 hours. Mesophilic lactic acid bacteria were analysed using MRS (de Man, Rogosa, Sharpe) agar according to ISO 15214:1998. Samples were incubated at 30 ± 1 ºC for 72 ± 3 hours. Following incubation, colony-forming units (CFU) were calculated using the colony counter Scan500 (Interscience, France).

- *pH determination.* The pH is determined according to the LVS ISO 2917:2004 standard. A SevenCompact S220 pH analyser (Mettler-Toledo GmbH, Switzerland) is used to read the values. The pH of each sample was measured in three replicates. The pH meter was calibrated with calibration solutions pH 10.00, pH 7.00 and pH 4.01.
- *Moisture content.* The moisture content was determined using the MA 50/1.R.WH device (RADWAG Wagi Elektroniczne, Poland), with an appropriate programme adjusted for each sample. The moisture content of each sample was measured in three replicates.
- *Water activity.* Water activity was determined according to ISO 18787:2017 - determination of water activity, by placing the dairy sample in a LabMaster-aw device (Novasina AG, Switzerland). Water activity was measured for each sample in triplicate (measurement range: 0.11 to 0.99 aw, accuracy: ± 0.01 aw). The measurement temperature was maintained at 22 ± 1 ºC.

Statistical analysis

Data acquisition and analysis were conducted using Microsoft Office Excel v16.0. Results are expressed as the mean ± standard deviation of three experiments unless specified otherwise. Statistical analysis was performed using the variance analysis method (ANOVA) and a t-test. A *p*-value of less than 0.05 ($P < 0.05$) was considered statistically significant.

Results and Discussion

Edible film coatings for cheese packaging

Due to the unique storage characteristics of cheese, packaging is considered as essential and crucial stage in the cheese production process. This is because packaging constitutes the final stage in the processing chain. If the packaging is improperly selected or becomes damaged during processing, transport, or storage, the effectiveness of prior processing steps may be compromised, even when those steps have been carried out correctly. Packaging that is specifically tailored to a product, taking into account factors such as material composition, barrier properties, and storage conditions, plays a crucial role in preserving quality and safety, while extending its natural shelf life or biological longevity (Patel, Modha & Ranganadham, 2017). Cheese is packaged using various materials based on the specific characteristics, processing conditions, storage requirements and intended use. The primary function of cheese packaging is to serve as a physical barrier that protects the cheese from mechanical damage and microbiological contamination, while preserving its quality to the highest possible standard (Han *et al.*, 2018).

Important considerations regarding the materials used for the cheese packaging are the toxicity of the material, compatibility with the cheese (does not give the cheese an uncharacteristic taste, smell, or colour), impact resistance, sanitation maintenance, protection against external light, aesthetic appeal, feasibility of printability and economic considerations as well shape, size and weight specifications (Rejeesh & Anto, 2023). Traditional packaging materials still commonly include aluminium foil laminated with paper, cellophane-paper composites, vacuum-sealed multilayer plastic films, semi-rigid films, and food-safe plastics such as PP (polypropylene), PE (polyethylene) and PVC (polyvinyl chloride). These materials ensure a barrier against moisture and oxygen, prevent spoilage and preserve the freshness of the cheese (Rejeesh & Anto, 2023). The use of non-biodegradable and non-edible materials, such as polyethylene, polyamide, and polypropylene, in cheese packaging raises ecological concerns and may be restricted by stringent regulations governing the migration of specific compounds from packaging materials into the cheese. Migration of specific compounds from coating materials is also a concern, particularly after application onto the cheese surface and subsequent solidification, which may lead to the migration of compounds from these materials into the cheese. These issues have prompted the industry to explore alternative packaging solutions, resulting in a surge of research into edible packaging materials (Aziz, Salama, & Sabaa, 2018; Costa *et al.*, 2018). The application of compostable or edible films as a substitute for petrochemical polymers is an engaging perspective since it ensures an alternative to nondegradable materials (Verbytskyi *et al.*, 2023). To reduce waste volume, biodegradable polymers are increasingly used, with packaging being one of their most important areas of application (Vroman & Tighzert, 2009). Table 2 presents the most commonly used biodegradable polymers in food packaging applications.

Table 2

Biodegradable polymers (Jouki *et al.,* 2013; Verbytskyi *et al.,* 2023)

Agricultural (Biomass) polymers	Polysaccharides: – Starch (potato, corn etc.); – Cellulose and cellulose derivatives (wood, straw), such as: · HPMC (hydroxypropyl-methylcellulose); · CMC (carboxymethylcellulose); · MC (methylcellulose). – Others: pectin; chitosan, gums, chitin; pullulan; rubbers. Proteins: – Animal origin: casein; albumin; whey proteins; collagen; gelatine; – Plant origin: zein; soy protein; gluten.
Microbial polymers	PHA (polyhydroxyalkanoates); PHB (polyhydroxybutyrate); PHBV (polyhydroxybutyrate-co-valerate).
Biotechnological polymers	Polylactates; PLA (Polylactic acid).
Oil refinery waste polymers	PCL (polycaprolactone); PEA (polyesteramide); PBSA (poly(butylene succinate-co-adipate)); PBAT (poly(butylene adipate-co-terephthalate)).

The potential and feasibility of using biodegradable materials in cheese packaging, particularly bioplastics, as innovative packaging solutions, is an area of growing interest. These materials can reduce environmental impact while maintaining the functionality needed to preserve cheese quality and safety (Verbytskyi *et al.,* 2023). Polymers such as nitrocellulose-coated cellophane and starch-based laminates are suitable for cheese packaging due to their effective gas barrier properties and excellent moisture resistance, which help preserve the cheese's freshness and overall quality (Patel, Modha & Ranganadham, 2017). Blending biodegradable polymers or biopolymers can ameliorate their essential properties (Vroman & Tighzert, 2009). These materials, generally PLA, do not show significant variations in quality, mechanical, and other technological properties out of conventional hydrocarbon based plastic packaging materials (Verbytskyi *et al.,* 2023). Fully biodegradable bioplastic packages made from starch and polylactic acid are already being produced; they are 20 times lighter than glass, 10 times more affordable than plastic, and free from synthetic plasticisers (Rejeesh & Anto, 2023; Holm *et. al.,* 2006).

The packaging technologies in cheese production are evolving and advancing to better align with the demands of consumers and the food sector. Recent innovations, such as modified atmosphere packaging, vacuum sealing, and antimicrobial coatings, aim to enhance product protection and extend shelf life. However, methods like biodegradable films and active packaging, which regulate moisture and inhibit bacterial growth, present challenges in maintaining product freshness. These innovative approaches should also enhance the safety and quality of cheese. Advanced packaging technologies must address consumer demands for food cost-effectiveness, safety, quality, information, and environmental sustainability in the global food packaging market (Rejeesh & Anto, 2023). Following widespread demand for new innovative packages with environmentally friendly properties, it would be necessary to produce edible biodegradable packaging for cheese, which preserves the sensory properties, as well as be capable of protecting cheese from the unpredicted effects of the external environment and moisture loss (Lopes *et. al.,* 2024). Recently, there has been growing interest in creating edible and compostable composed coatings and films for environmental reasons, as well as due to the costs and supply of petroleum materials.

Ingredients used to develop biodegradable films and coatings are generally divided into the categories of polysaccharides, lipids, proteins, microbial polyesters and polyurethanes (Marcet, 2023; Zhang & Sablani, 2021). Edible coatings are micro-thin layers comprised of different edible components (Yaashikaa *et al.,* 2023).

Polysaccharides based films

Derived from starch (native or modified), gums (guar, acacia, tragacanth, etc.), cellulose, pectin, alginate extracts, carrageenan, agar, pullulan and chitosan exhibit a unique set of properties. While they provide limited protection against humidity, they demonstrate controlled diffusion to oxygen and carbon dioxide, along with fats and oils resistance. Among polysaccharides, starch stands out as a particularly promising biopolymer material due to its abundance, affordability, biodegradability, non-toxicity and renewability. Study on starch-based film production has explored a wide range of sources, including, agar, sago, bananas, cassava, peas, corn, maize, rice, kudzu, yams and potatoes. However, challenges arise with pure starch-based films. They tend to exhibit weak mechanical properties and dimensional stability, often characterised by surface cracks and fragility. To address these shortcomings, researchers have investigated the incorporation of plasticisers, such as sorbitol, urea, polyethylene, formamide, glycol and glycerol into pure starch formulations. These additives enhance workability and mitigate film brittleness. Nevertheless, pure starch is susceptible to retrogradation, a procedure where degraded amylopectin chains and amylose monomers reassociate to create more organised structures in the gelatinised starch mixture. This phenomenon can adversely affect the sensory and storage qualities of dairy products (Dinika *et al.*, 2020; Sanyang *et al.*, 2015; Wang *et al.,* 2015).

Lipid based films

To achieve desirable biofilm characteristics, such as increasing hydrophobicity, lipid-based films are commonly blended with hydrocolloids, including cellulose, starch, and protein derivatives. These films are typically formulated using a wide range of lipid sources, including oils and fats of both vegetable and animal origin, such as palm, peanut, coconut, cocoa, and butter, fatty acids, and monoacylglycerols, diacylglycerols, and triacylglycerols. Waxes, such as jojoba, candelilla, carnauba, paraffin, and beeswax, along with natural resins like chicle, olibanum, and guarana, also contribute to the formulation. Furthermore, the incorporation of emulsifiers and surface-active agents, including fatty acids, fatty alcohols, and lecithin, aids in achieving the desired properties of lipid-based biofilms (Galus & Gadzinska, 2015).

Protein-based films

Films offer an appropriate solution for hydrophilic product surfaces, providing efficient barriers against O_2 and CO_2 while facing limitations in water resistance. To enhance water protection, hydrophobic materials, such as beeswax or oleic acid can be incorporated, while flexibility can be improved with the addition of plasticisers, such as polyethylene glycol or glycerol. A diverse array of protein sources can serve as the foundation for these biofilms. Animal-derived proteins include whey protein concentrate, gelatine, casein, egg albumin, and isolated collagen. Plant-based options encompass peanut, wheat proteins, soybeans, rice, cottonseed and corn. Besides, in the cheese production, the residue known as whey holds significant value. It contains bioactive proteins with antimicrobial properties, such as bioactive peptide fragments, and lactoferrin, which may be released through the enzymatic hydrolysis of proteins like β-lactoglobulin and α-lactoalbumin. Incorporating cheese whey-derived components, particularly lactoferrin, into edible film composites presents an opportunity to prolong perishable cheese shelf-life. Lactoferrin, known for its broad-spectrum antimicrobial activity against Gram-negative and Gram-positive microorganisms, enhances the efficacy of these edible films in preserving cheese safety and quality (Chen *et al.*, 2019; Dinika *et al.*, 2020; Lappa *et al*., 2019).

Edible packaging can be applied using various methods, depending on its form. For coatings, techniques, such as electrostatic spraying, dipping, spraying, and brushing can be used, while films are typically applied through individual wrapping. The optimal application method should ensure complete coverage of the cheese, thereby enhancing shelf life (Zhong *et al.*, 2014). Moreover, these coatings provide shielding against UV radiation, manage moisture levels, and uphold the internal balance between solutes and gases crucial for the ripening and respiration processes of perishable products. They are carriers for various bioactive compounds, including natural antimicrobials, phenolic compounds and antioxidants, thereby enhancing their efficacy in cheese preservation and inhibiting microbiological activity on the cheese surface (Yaashikaa *et al.,* 2023).

Several relevant aspects required for an optimal edible film are outlined in the literature (Kumari *et al.*, 2017; Rawdkuen, 2019), including the following: (1) It must be free from allergens, indigestible substances and toxins; (2) Needs structural stability to prevent damage during transport and handling; (3) Must adhere well to food surface evenly; (4) Controls water migration to maintain desired moisture; (5) Provides semi-permeability for gas balance, preventing spoilage; (6) Preserves flavour, nutrition, and appearance without alteration; (7) Ensures microbial safety and prevents decay; (8) Can be supplemented with nutrients, vitamins, flavours, and colours; (9) Restricts additives on the surface to minimise cost and taste intrusion; (10) Manufacturing should be simple and cost-effective.

Edible coatings have emerged as a promising solution for cheese preservation, offering benefits, such as increased shelf life, improved texture, and enhanced sensory qualities, particularly in flavour and aroma. These coatings also help decrease plastic waste and environmental impact, making them a sustainable option for cheese packaging (El-Sayed & Youssef, 2024). There are several references summarised available (see Table 3) on the developed edible biodegradable materials, which would be suitable for cheese packaging.

Table 3

Developed edible films and coatings for customisable cheese packaging

Film composition	Product	Main findings of the study	Reference
Natamycin; Hydroxyethyl-cellulose	Mozza-rella cheese slices	Incorporating natamycin into hydroxyethylcellulose films reduced *Penicillium spp.* growing and extended cheese slice shelf life. This suggests that using natamycin-containing films as a biodegradable antifungal system is a viable option for cheese packaging, enhancing food safety without compromising quality.	Torrijos *et al.*, (2022)
Pullulan, chitosan, gelatine, lemongrass and curry plant hydrolats	Sliced cheese	Studies have shown that combining biopolymers such as pullulan with chitosan or gelatine can enhance mechanical and barrier properties, which could be adapted for other dairy products. Incorporating antimicrobial agents, such as curry plant hydrolats, into coatings have proven effective in cheese and could be explored for other dairy products to prevent spoilage.	Erceg *et al*., (2024)
Chitosan; Sodium alginate; Carboxymethyl cellulose; Antimicrobial microcrystalline cellulose; *Bifidobacterium lactis*, *Lactobacillus acidophilus*, *Lactobacillus casei*	Ultra-Filtrated soft cheese	The probiotic edible films effectively inhibited all tested microorganisms, with particularly strong antimicrobial effects observed in films containing chitosan and sodium alginate. Over 45 days, cheese treated with probiotic edible coatings, sodium alginate, carboxymethyl cellulose, and chitosan, was evaluated chemically, microbiologically and sensorily. The results showed decreased dry matter, protein, and fat content for cheeses coated with sodium alginate and carboxymethyl cellulose. However, *Bifidobacterium lactis*, *Lactobacillus acidophilus*, *Lactobacillus casei* remained high (> 8.0 $\log_{10}$ CFU g^{-1}) across all films after 45 days. Films containing sodium alginate and chitosan effectively protected cheese from spoilage, with sensory scores indicating their superior overall acceptability compared to control. Consequently, the formulation of antimicrobial edible coatings shows potential for controlling spoilage and ensuring product stability in soft cheese applications.	El-Sayed *et al.*, (2021)
Sodium caseinate; Nisin	Cheese (mini red Babybel^{R})	*Listeria innocua* was analysed in surface-inoculated cheese samples. This extends the shelf life of cheeses and potentially improves microbiological safety.	Cao-Hoang *et.al*., (2010)
Potato peels; Quince peels; Starch; Glycerol	Cured cheeses	Results showed that the film with potato and quince increased cheese hardness. Microbial analysis indicated minimal growth of moulds and yeast compared to the natamycin treatment. Coatings did not affect the quality of the cheese's sensory properties.	Coimbra *et. al*., (2023)

Pectin; acid whey proteins; *Lactobacillus helveticus, Lacticaseibacillus paracasei*	Gouda cheese	The paper highlights the successful production of a pectin-based edible coating for Gouda cheese, which combined with biodegradable packaging, showed protective properties against spoilage.	Aleksandrovas *et al*., (2024)
Locust bean (carob) flour; Potato starch	Norvegia® original cheese	New bioplastic films seal and preserve cheese slices. After 21 days, the cheese slices remained mould-free, comparable to those in petroleum-based packaging. Despite slight dehydration (~10% weight loss), cheese texture has remained unchanged. After 7 days, evaluated volatile compounds' profile indicated the initiation of the oxidation process in cheese. These films provide water absorption, UV protection, and antioxidant properties, ideal for storing fatty foods.	Lopes *et.al.,* (2024)
Whey protein concentrate; Casein	Cheddar cheese	Casein films have excellent stretching properties. Films with whey protein concentrate improve oxygen permeability. The sensory properties of Cheddar cheese were found to remain unaffected and have a potential to extend the shelf life of cheese.	Wagh *et. al.*, (2014)
White tea extracts; Yerba mate; Furcellaran-whey protein isolate	Fresh soft rennet-curd cheese	During storage, the total bacterial count in the cheese decreased, along with the reduction in water content and water activity. In contrast, these parameters remained stable in the control cheese coated with linear low-density polyethylene (LLDPE).	Pluta-Kubica *et. al.*, (2022)
Acetic acid; Glycerol; Nisin-silica liposomes or nisin liposomes; Chitosan	Cheddar cheese	Chitosan-coated nisin-silica liposome film represented the antibacterial activity against *L. monocytogenes* without altering the sensory properties of cheese.	Cui *et al*., (2016)
Single cell protein from cheese whey; Glycerol	not tested on cheese	Development of novel edible films from single-cell protein derived from cheese whey, highlighting its potential for sustainable packaging.	Koukoumaki *et al*., (2024)
Essential oils from *Laurus nobilis* and *Rosmarinus officinalis;* Zein from maize	Semi-hard cheese slices	Films against *Listeria monocytogenes, Staphylococcus aureus,* and total plate counts of microorganisms were tested. Essential oils originating from *Laurus nobilis* showed higher antibacterial activity compared to *Rosmarinus officinalis*.	Goksen *et. al.*, (2020)
Chitosan; Whey proteins	Ricotta cheese	It was observed that the packaging exhibited 21% higher carbon dioxide permeability, 35% lower oxygen permeability, and three times higher water vapor permeability compared to petroleum-based plastic. Additionally, it resulted in reduced counts of mesophilic, psychrotrophic, and lactic acid bacteria, contributing to a prolonged shelf life of Ricotta cheese.	Di Pierro, *et al*., (2011)
Carrageenan; Glycerol; Terminalia bellerica	Himalayan cheese (Kalari)	*T. bellerica* enhanced coating density and thickness, while decreasing water-vapor transmission rate, solubility, and transparency. This film improves cheese storage stability for commercial use, resulting in lower lipid oxidation and microbial count. Consequently, cheese samples coated with *T. bellerica* exhibited higher sensory quality.	Kouser *et al*., (2023)

Polylactic acid	Semi-hard cheese (Danbo cheese)	The findings suggest that to protect semi-hard cheese from moisture loss and lipid oxidation when packaged with polylactic acid, it is recommended to store the cheese in dark conditions or use non-transparent materials, while also minimising the water vapor transmission rate.	Holm *et al.,* (2006)
Mandarin fibre; Oregano essential oil; Tween 80; Sodium alginate	Low-fat cheese (CADICOOP light)	This coating offers a promising alternative to enhance the coated cheese pieces nutritional value. Furthermore, edible coatings containing at least 2.0% (w w^{-1}) oregano essential oil have been shown to enhance the microbial stability of cheese pieces by inactivating pathogens such as *Staphylococcus aureus,* while also preserving the visual appearance of the product over time. Consequently, the use of nanoemulsion-based edible coatings with oregano essential oil extends the low-fat cheese shelf life.	Artiga-Artigas *et al.*, (2017)
Bifidobacterium animalis subsp. *lactis* BB-12®; Sodium caseinate; Inulin; Fructooligosaccharide	Fresh block-type processed cheese from Adıyaman province (Türkiye)	The study demonstrated that sodium caseinate-based edible films containing *Bifidobacterium animalis subsp. lactis* BB-12®, optimised with inulin and fructooligosaccharide, can effectively improve the quality of processed cheese. These films reduced weight loss, preserved softness and colour, and maintained probiotic viability during storage. The optimal formulations ensured stable drying and retained viable probiotic counts of 4 – 5 Log_{10} CFU g^{-1} after storage. The findings suggest these films are promising carriers for probiotics, enhancing product quality and extending shelf life.	Ceylan & Atasoy (2022)
Various antimicrobial compounds; Guar gum; Glycerol; Sunflower oil; Whey protein isolate	Semi-hard cheese Queijo Saloio (Torres Vedras, Portugal)	The application of antimicrobial edible coatings on cheese resulted in a 10% (w/w) reduction in water loss. Additionally, these coatings inhibited the growth of pathogenic microorganisms, such as *Listeria monocytogenes*, *Enterobacter* species, *Escherichia coli*, and *Pseudomonas* species. Growth of beneficial lactic acid bacteria remained stable throughout the storage period.	Ramos *et al.*, (2012)

Information summarised in the Table 3, can be observed that several studies have been performed out on cheeses with coatings and edible films of different compositions, intended to improve the cheese preservation due to storage and transportation processes. However, no single composition has been identified that comprehensively addresses all the requirements for edible packaging to perform its intended functions fully. Most compositions primarily fulfilled specific properties, while disregarding other essential aspects of quality and safety. For instance, while some effectively controlled the growth of undesirable microorganisms, they lacked control against mechanical properties and moisture permeability and other factors. Researchers have used glycerol in biodegradable film production. It is a plasticiser one of the most used ingredients for creating biofilm due to its ability to form gel in specific conditions. It has been effectively employed to create oxygen-proof, transparent, waterproof and flexible biofilms (Kouser *et al.,* 2023; Ramos *et al.*, 2012). Besides Saez-Orviz *et al.*, (2022) created film with *Lactobacillus plantarum* and lactobionic acid, obtaining edible film with probiotic and prebiotic properties, which would be suitable for cheese packaging. Jouki et al. (2013) developed edible film using glycerol mixed with cress seed carbohydrate gum and found that the glycerol content significantly influenced the film's barrier properties. It improved flexibility, prevented cracks, and eased handling; however, further enhancement is needed to achieve complete water vapor impermeability, a critical requirement for cheese packaging.

To ensure the quality of cheese packaging, it is necessary to develop a biodegradable film with improved antimicrobial properties, reduced water

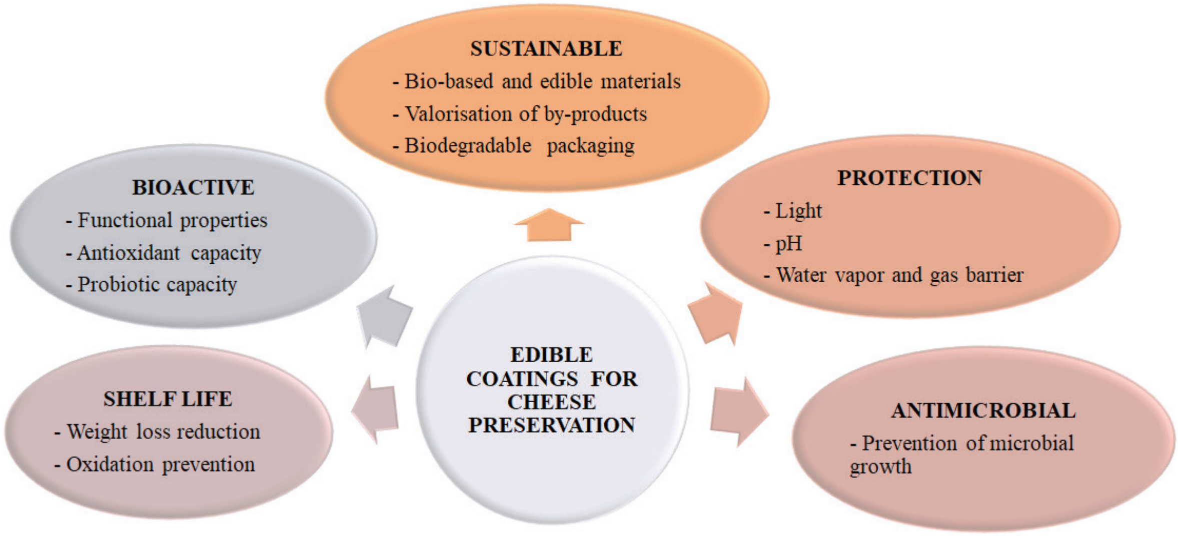

Figure 2. Guidance for edible coatings for cheese preservation (Costa *et al.,* 2018).

vapor permeability, and mechanically more flexible or durable. The proposed strategy for edible coatings for cheese packaging is displayed in Fig 2.

The antimicrobial effectiveness of bioactive agents used in packaging diminishes over time, which is a significant limitation in the use of antimicrobial films. To enhance the antimicrobial properties of packaging, chemical preservatives, including sulphites, organic acids, alcohols, chlorides, phosphates, nitrites, epoxides, hydrogen peroxide are commonly employed (Patel, Prajapati, & Balakrishnan, 2018). Chitosan is an organic polymer that is a biodegradable and non-toxic polysaccharide with strong antimicrobial properties. Chitosan, enriched with antifungal agents, such as natamycin, significantly reduces the growth of fungi, yeast, or mould on the surface of cheese (Han *et al.,* 2018; Rejeesh & Anto, 2023).

During the experimental study in the Latvian and Ukrainian project "Enhanced use of environment-friendly biodegradable packages for dairy products (BIOPACK Dairy)" in 2023 implementation, the soft cheese Kleo (manufactured in Latvia Ltd. "Rankas piens") was studied (Verbytskyi *et al.,* 2023). The cheese sample was packed in the coating film Ceramis®-PLA-SiOx (polylactic acid-silicone oxide) with a thickness of 50 ± 2 µm, that had been recognised as the first biodegradable polylactic acid film with improved barrier properties (Dukalska *et al.,* 2013). However, the study on soft cheese packaging using Ceramis®-PLA-SiOx coating film yielded unsatisfactory results, as the material exhibited gas and moisture permeability that limited the shelf life of the perishable cheese to only 10 days. With the Latvian and Ukrainian project "Enhanced use of environment-friendly biodegradable packages for dairy products (BIOPACK Dairy)" it is necessary to use polylactic acid films with other polymeric biodegradable materials to achieve the desired result of qualitative storage of dairy products (Verbytskyi *et al.,* 2023). However, the use of edible materials in the dairy food industry still faces challenges, including: (1) their potential impact on dairy product colour and flavour, which may restrain consumers (although not all coatings and films exhibit this issue); (2) difficulties in achieving a homogenous food surface covering; (3) the requirement for higher amounts of natural active compounds in coatings; (4) the cost of materials, which can elevate the overall application cost in the dairy industry (Costa *et al.*, 2018). Edible biodegradable packages developed so far do not meet all requirements to maintain dairy product quality during storage, thus it would be advisable to combine those films to reach the optimal storage quality of products. It is assumed that edible and environmentally friendly packaging materials will propel emerging trends and advancements in packaging technology. Consequently, integrating sustainable packaging systems with advanced processing techniques to improve food safety and shelf life is expected to be a prominent area of research in the near future (Rejeesh & Anto, 2023).

To address these challenges and advance the field of edible biodegradable coatings for dairy packaging, further research is needed. Studies investigating the effects of various coating formulations, application methods, and storage conditions on product quality and safety are essential for effective packaging solutions. Additionally, research efforts should focus on optimising the physical properties of edible coatings to ensure their compatibility with products. Collaborative initiatives involving food scientists, packaging engineers and industry stakeholders will be instrumental in driving innovation and facilitating the adoption of sustainable packaging practices in the dairy industry.

Current research of dairy product biodegradable packaging

The analysis of studies conducted in Latvia and Ukraine indicates that consumers possess limited knowledge and a relatively underdeveloped attitude toward biodegradable packaging. This is reflective of broader global trends where consumer awareness and attitudes towards sustainable packaging are still evolving. The transition to biodegradable packaging is shaped by multiple factors, including consumer perceptions, economic feasibility, and access to reliable information (Muizniece-Brasava & Kirse-Ozolina, 2018; Verbytskyi *et al*., 2024). Verbytskyi *et al.* (2024) found that demand for biodegradable packaging is growing, particularly among environmentally conscious consumers. However, high costs, limited availability, and insufficient awareness remain significant barriers to widespread adoption. Both Ukrainian and Latvian consumers support biodegradable packaging, emphasising the need for it to align with the environmental qualities of the products it contains. Government support through legislative initiatives and awareness campaigns is essential to promote biodegradable materials as viable alternatives to traditional plastics. The study highlights strong public interest in a wider range of packaging options and better access to information on their environmental and health benefits, as well as broad support for policies that incentivise their adoption in the food industry (Verbytskyi *et al*., 2024).

Cheese is one of the most popular dairy products, requiring long-term storage solutions compared to other dairy items. However, sustainable and environmentally friendly packaging materials are essential for all dairy products (Zambujal-Oliveira & Fernandes, 2024). Unlike cheese, other dairy products, such as yoghurt, have different textures, moisture content, and spoilage mechanisms, requiring tailored coating solutions (Aleksandrovas *et al*., 2024; El-Sayed & Youssef, 2024). Since it is quite challenging to develop an edible biodegradable coating for other dairy products, as has been done for cheese (Jurić *et al*., 2024). A study in Latvia is currently underway to design biodegradable packaging for various dairy products, moving a step closer to the goal of sustainable and environmentally friendly packaging. This study identifies and tests materials that not only preserve the quality and shelf life of dairy products, such as cheese, yoghurt, cottage cheese, sour cream, and butter, but also align with sustainability goals. The study indicates that the advancement of biodegradable materials for dairy products should precede the creation of edible coatings. Coatings are particularly well-suited for solid dairy products but present greater challenges when applied to other dairy products due to their composition. In developing high-performance packaging for dairy products, initial emphasis should be placed on biodegradable materials to support environmentally sustainable solutions.

In dairy production and packaging, different dairy products present varying levels of sensitivity to light, oxygen, and temperature due to their unique compositions. Among these, some products are relatively easier to package, while others require more specialised solutions to ensure their quality and shelf life (Talha *et al*., 2024). Cottage cheese also requires refrigeration and oxygen-resistant packaging to maintain freshness. Its high moisture content makes it prone to microbial growth, necessitating an airtight environment. The packaging needs to prevent oxygen ingress, which could accelerate spoilage and compromise the product's quality. Typically, cottage cheese is stored in plastic with sealed lids, which offer the necessary barrier to oxygen and maintain moisture (Prajapati *et al*., 2023; Talha *et al*., 2024). Yoghurt requires a sealed, oxygen-impermeable container to protect it from contamination and spoilage. However, yoghurt is generally less sensitive to light and temperature compared to some other dairy products. The fermentation process and active lactic acid bacteria microbiota in yoghurt inhibit undesirable flora, making it more resilient than products with lower pH (Talwalkar & Kailasapathy, 2004; Zhang *et al.,* 2024). Semi-hard cheese is also sensitive to light and oxygen exposure, as these factors can lead to flavour degradation and spoilage. Semi-hard cheeses are often packaged with wax coatings, vacuum-sealed plastic, or other protective layers to minimise light and oxygen exposure (El-Sayed & Youssef, 2024). Butter, on the other hand, requires specialised packaging that offers a strong barrier to both light and oxygen, such as foil-lined paper or opaque, grease-resistant wrappers (Basheer & Muthusamy, 2022; Nekera et al., 2023). Therefore, tests were conducted using different packaging materials to determine which ones best meet the stringent requirements of dairy product packaging.

Test results of dairy storage in biodegradable packaging

While it can be observed that all the tested packaging materials (numbers 2, 3, and 4 in Fig. 1) are transparent, it is important to conduct tests pH determination (see Fig. 3), MAFAm count (see Fig. 4), lactic acid bacteria count (see Fig. 5), moisture content (see Fig. 6), water activity determination (see Fig. 7) to evaluate whether materials selected affects product quality.

pH determination during storage

The pH changes observed in the samples during storage indicate that in butter samples (E), the pH significantly increased over time, while in yoghurt (B), semi-hard cheese (C) and cottage cheese (D) samples, the pH significantly decreased during storage. In contrast, the pH of sour cream samples (A) showed a slight increase. Among the sour cream (A) samples, SC2, SC3, and SC4 ($p<0.05$) showed a lower pH at the end of storage compared to the SC1 sample in its original packaging ($p>0.05$). No significant differences were observed between the packaging materials of the yoghurt (B) samples; however, for the semi-hard cheese (C) samples, the significant pH decrease during storage was noted in the HC2 sample, while the pH decrease in the original packaging HC1 was less pronounced. Similar to the semi-hard cheese samples, the cottage cheese (D) samples showed the lowest pH values in CC2, CC3, and CC4, with no statistically significant differences among them ($p<0.05$). However, the CC1 sample in its original packaging exhibited a significant difference, as its pH was not as low as that of the other samples. For the butter (E) samples, the highest pH increase was observed in the B4 sample, followed

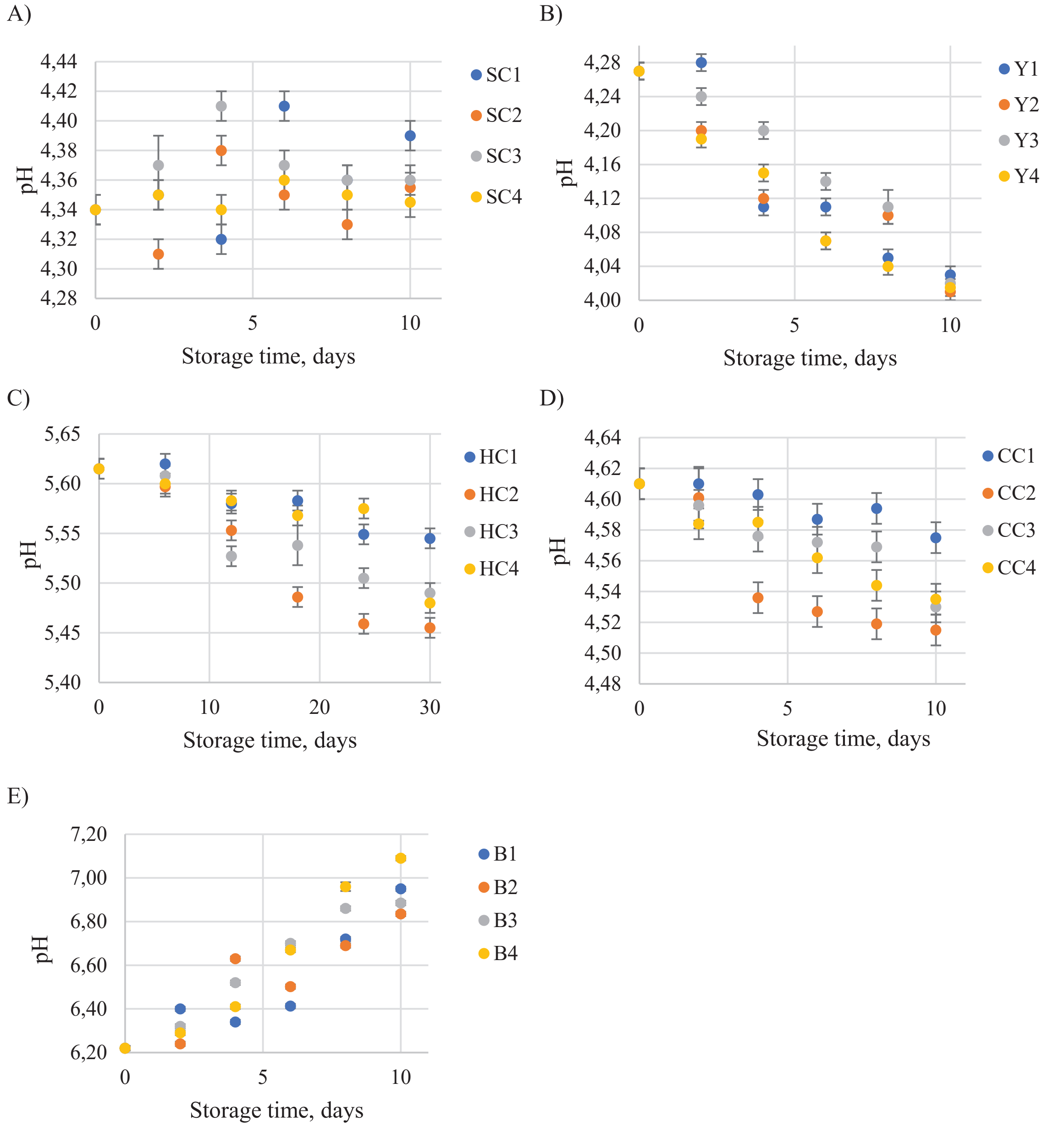

Figure 3. pH changes in dairy products: 20% sour cream (A – SC1, SC2, SC3, SC4); 3% natural yoghurt (B – Y1, Y2, Y3, Y4); semi-hard cheese (C – HC1, HC2, HC3, HC4); 9% cottage cheese (D – CC1, CC2, CC3, CC4); 82% butter (E – B1, B2, B3, B4), during storage.

by B1 and B3, with the lowest pH recorded in the B2 sample. Significant differences were found between all the butter samples ($p>0.05$).

Mesophilic aerobic and facultatively anaerobic microorganism (MAFAm) determination during storage

An increase in MAFAm concentration was observed in all samples during storage (Fig. 4). In the sour cream (A) samples, the highest concentration of MAFAm was observed in the SC4 sample, while the lowest was found in SC1 and SC2 samples ($p<0.05$). In the yoghurt (B) samples, there were no significant differences between the samples at the end of storage ($p<0.05$). In the semi-hard cheese (C) samples, it was evident that the HC2 and HC1 samples contained significantly lower amounts

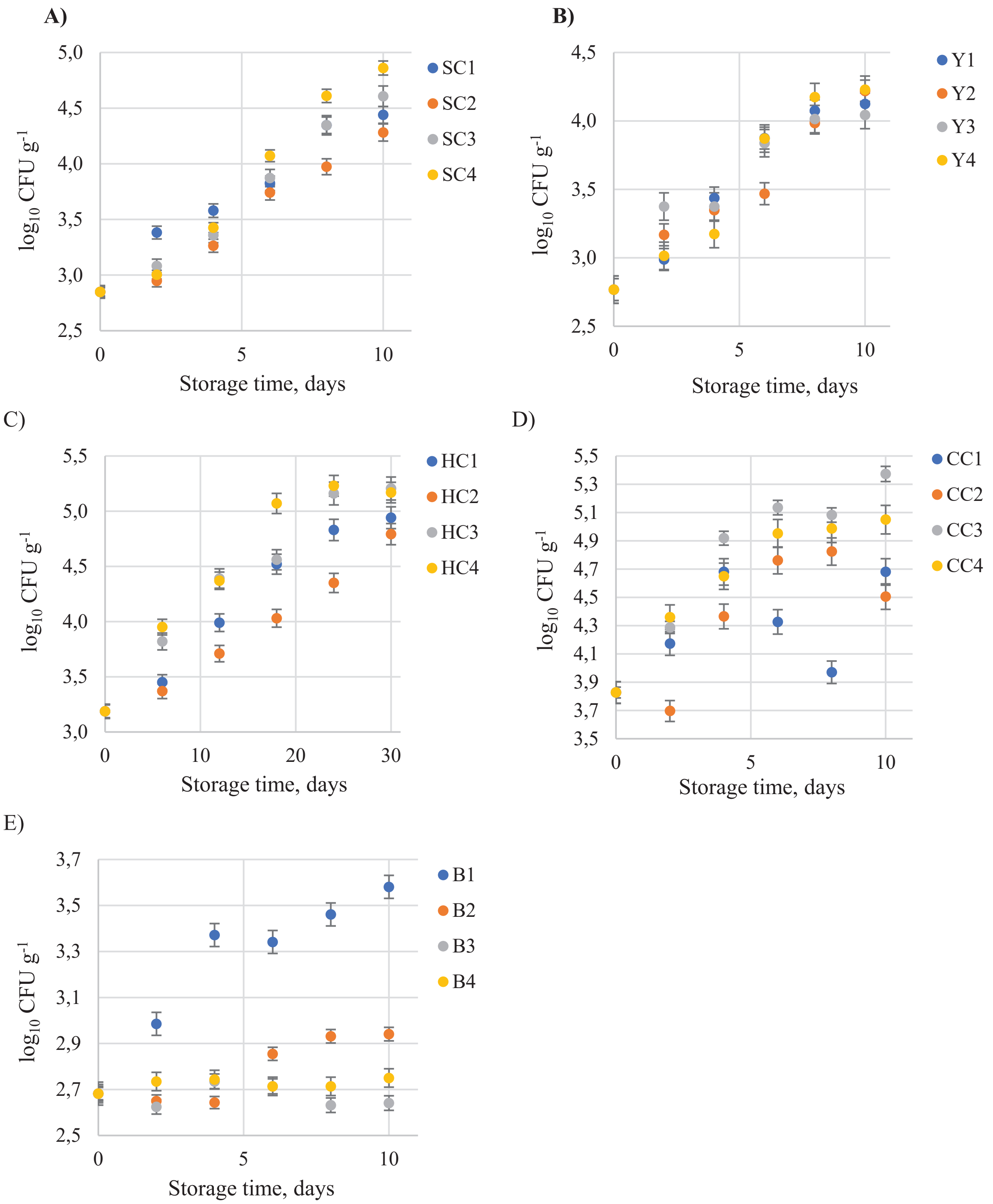

Figure 4. MAFAm count in dairy products: 20% sour cream (A – SC1, SC2, SC3, SC4); 3% natural yoghurt (B – Y1, Y2, Y3, Y4); semi-hard cheese (C – HC1, HC2, HC3, HC4); 9% cottage cheese (D – CC1, CC2, CC3, CC4); 82% butter (E – B1, B2, B3, B4), during storage.

of MAFAm compared to the HC3 and HC4 samples. A similar trend was observed in the cottage cheese (D) samples. In contrast, in the butter (E) samples, a noticeable increase in the MAFAm count was observed in the control sample B1, as well as in B2, while no significant changes in the MAFAm count were seen in the B4 and B3 samples from the initial storage day.

Lactic acid bacteria determination during storage

The changes in lactic acid bacteria are shown in Fig. 5. In the sour cream (A) samples, the number of lactic acid bacteria increased, except for the SC2 sample, where it remained unchanged (p<0.05). Significant increase was observed in the SC4 sample. In the yoghurt (B) samples, the number of lactic acid

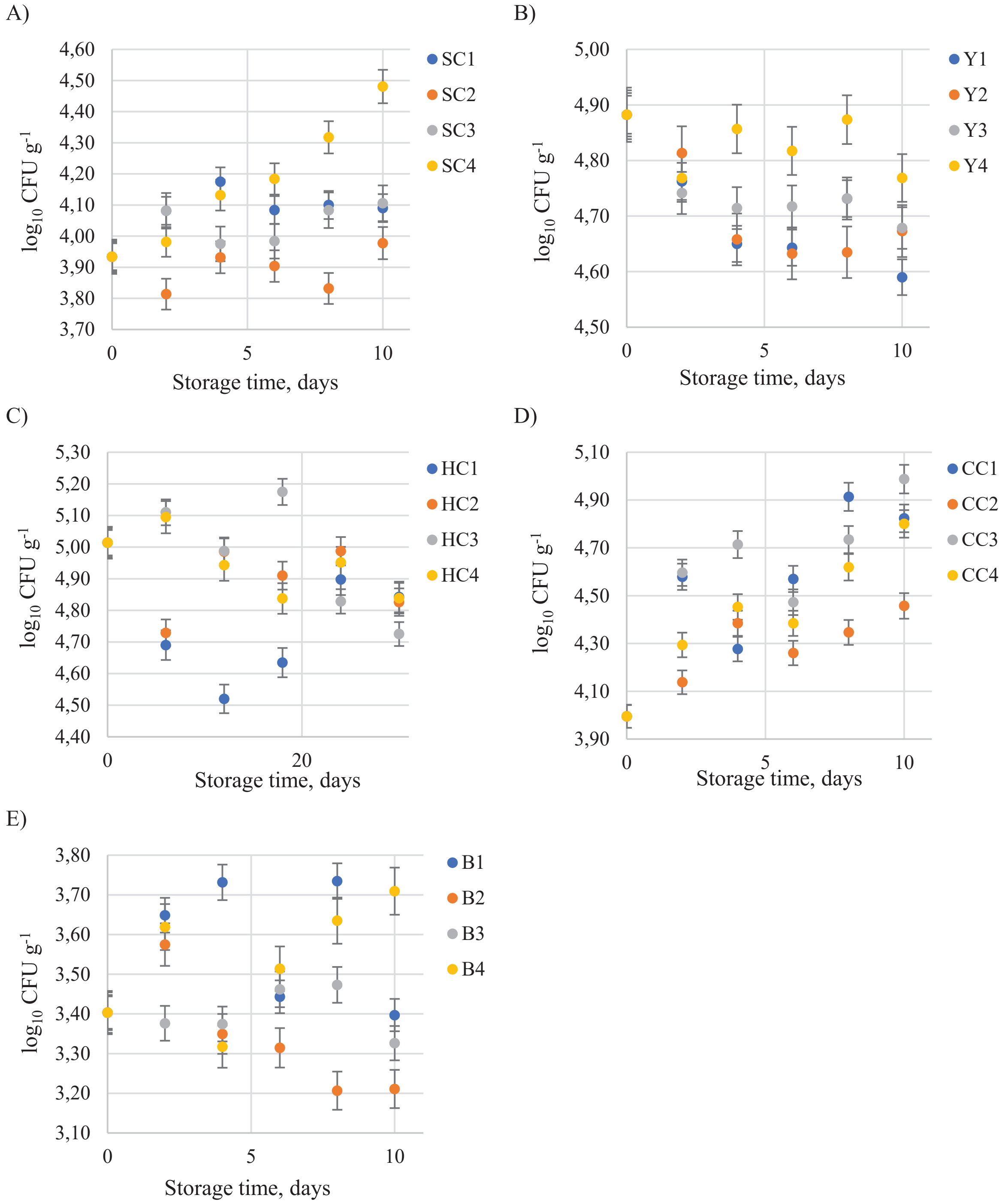

Figure 5. Lactic acid bacteria count in dairy products: 20% sour cream (A – SC1, SC2, SC3, SC4); 3% natural yoghurt (B – Y1, Y2, Y3, Y4); semi-hard cheese (C – HC1, HC2, HC3, HC4); 9% cottage cheese (D – CC1, CC2, CC3, CC4); 82% butter (E – B1, B2, B3, B4), during storage.

bacteria significantly decreased during storage in all samples. The smallest decrease was observed in the Y4 sample, while a significant reduction was noted in the other samples. In the semi-hard cheese (C) samples, the number of lactic acid bacteria decreased in all samples. No significant differences were observed in the lactic acid bacteria CFU between HC1, HC2, and HC4 during storage (p<0.05), but a significantly lower number of lactic acid bacteria was observed in the HC3 sample. In contrast, in the cottage cheese (D) samples, the number

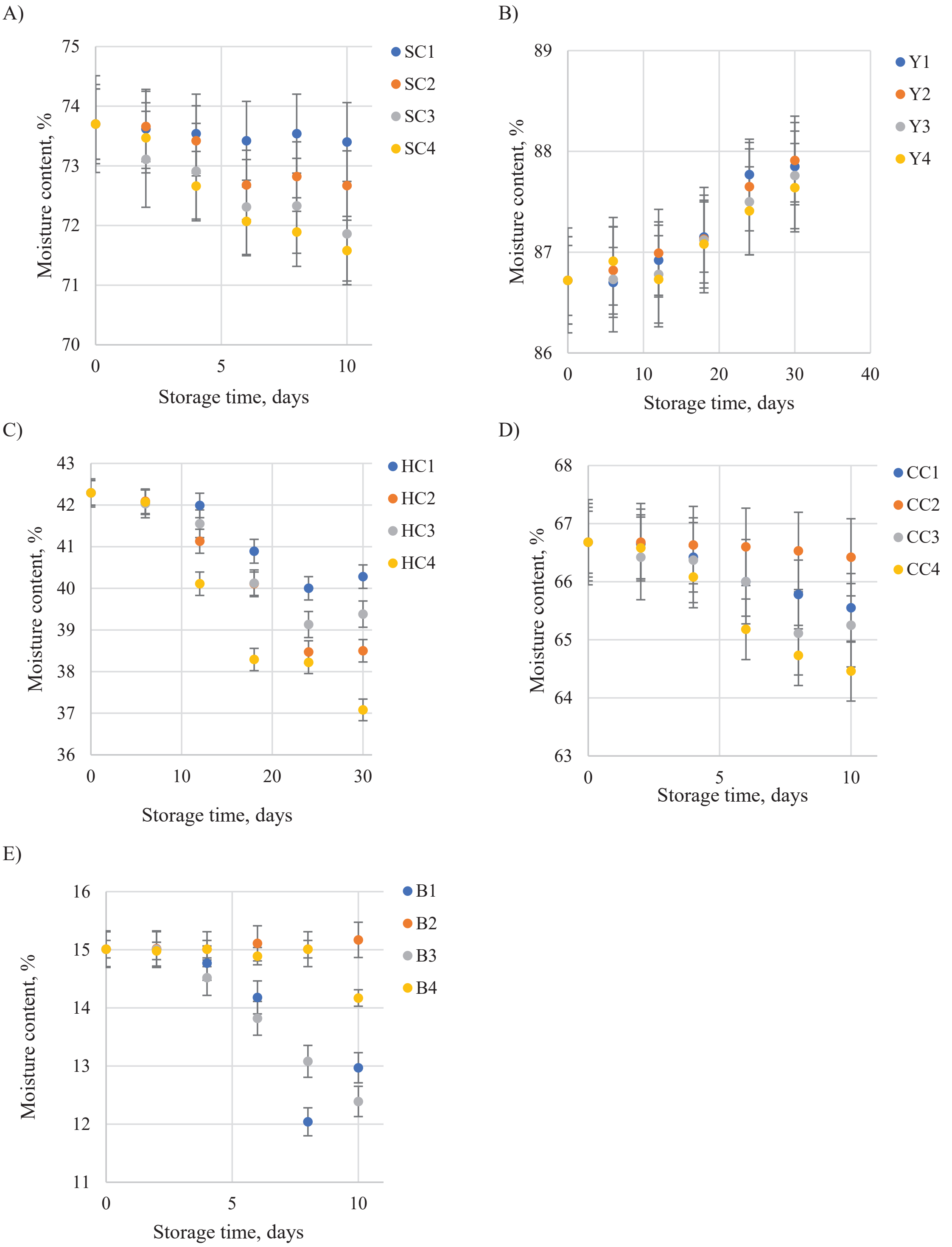

Figure 6. Moisture changes in dairy products: 20% sour cream (A – SC1, SC2, SC3, SC4); 3% natural yoghurt (B – Y1, Y2, Y3, Y4); semi-hard cheese (C – HC1, HC2, HC3, HC4); 9% cottage cheese (D – CC1, CC2, CC3, CC4); 82% butter (E – B1, B2, B3, B4), during storage.

of lactic acid bacteria increased. The smallest increase was observed in the CC2 sample compared to the other samples. In the sour cream (E) samples, the number of lactic acid bacteria increased in the B4 sample, while it decreased in the B2 and B3 samples. The control sample B1 showed no change in the number of lactic acid bacteria compared to the first day of storage.

Moisture content determination during storage

The moisture content (Fig. 6) did not significantly change in the SC1 and SC2 samples during storage; however, slight decreases in moisture content were observed in the SC3 and SC4 samples. In the yoghurt (B) samples, minor changes in moisture content were noted, with a slight increase in all samples, but no significant differences were observed between the samples at the end of storage ($p<0.05$). In all semi-hard cheese (C) samples, the moisture content decreased. A notable decrease in moisture was observed in the HC4 sample. The best moisture retention was found in the control sample HC1, followed by the HC2 and HC3 samples. In the cottage cheese (D) samples, the moisture content did not significantly change during storage ($p<0.05$), except for the CC4 sample, where it slightly decreased. In the butter (E) samples, it was observed that the moisture content in the B2 sample remained unchanged during storage, while it slightly decreased in the B4 sample and significantly decreased in the B1 and B3 samples.

Water activity determination during storage

As shown in Fig. 7, water activity in the sour cream (A) samples remained unchanged in SC1 and

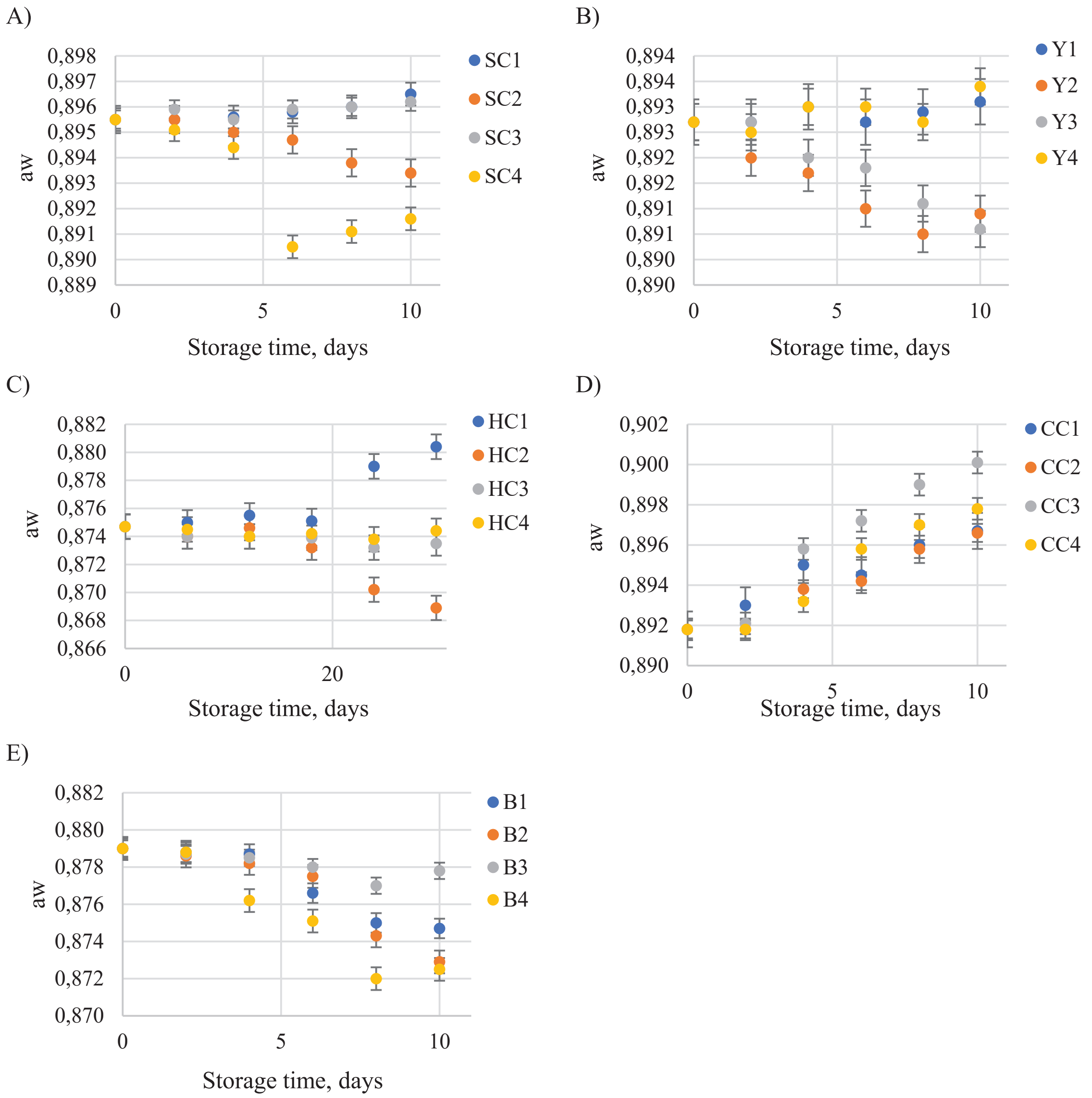

Figure 7. Water activity changes in dairy products: 20% sour cream (A – SC1, SC2, SC3, SC4); 3% natural yoghurt (B – Y1, Y2, Y3, Y4); semi-hard cheese (C – HC1, HC2, HC3, HC4); 9% cottage cheese (D – CC1, CC2, CC3, CC4); 82% butter (E – B1, B2, B3, B4), during storage.

SC3, but decreased in SC2 and SC4. In the yoghurt (B) samples, water activity slightly increased in the Y1 and Y3 samples, while it decreased in the Y2 and Y4 samples. In the semi-hard cheese (C) samples, water activity remained constant in HC2 and HC3, increased in the control sample HC1 and decreased in HC4. In the cottage cheese (D) samples, water activity increased during storage, with the most significant increase observed in the CC3 sample, while the other samples did not show significant differences (p<0.05). In the butter (E) samples, water activity decreased in all samples.

pH and microbiological changes in dairy products are closely interconnected, with variations influenced by product type, composition, and storage conditions. In sour cream, pH changes during storage are primarily driven by the lactic acid bacteria (LAB), which produce lactic acid through fermentation (Musiy *et al.,* 2017). Similarly, in natural yoghurt, post-acidification continues during storage as LAB remains active, generating lactic acid and causing a gradual decline in pH (Deshwal *et al.*, 2023). For semi-hard cheese, pH during storage is affected by the biochemical reactions occurring during ripening. While semi-hard cheeses generally maintain a stable pH as a result of their lower moisture content and reduced microbial activity, slight fluctuations may still occur due to biochemical processes such as proteolysis and lipolysis (Brandielli *et al.*, 2020). Cottage cheese, with its high moisture content, exhibits more pronounced pH decreases during storage as residual microbial activity, particularly from LAB, ferments remaining lactose into lactic acid, further lowering the pH (Makhal *et al.,* 2015). In contrast, butter's low water content results in pH changes during storage; however, slight increases may occur due to the degradation of acidic components, potentially impacting quality (El-Safety *et al.,* 2017). External factors, such as oxygen and light exposure, also significantly affect pH dynamics. Oxygen exposure can promote aerobic microbial growth or oxidative reactions in dairy products, indirectly influencing pH. In cottage cheese and yoghurt, oxygen may stimulate spoilage microorganisms, accelerating acid production and further reducing pH, while in butter lipid oxidation can generate alkali by-products, slightly increasing pH over time. Light exposure can degrade fats, proteins, and other components in dairy products, enhancing microbial activity and causing pH changes. For instance, light-induced oxidation of fats and proteins can produce off-flavours and acidity, while in semi-hard cheese, light can degrade vitamins and lipids, triggering oxidative stress and biochemical reactions that impact pH stability. These findings highlight the critical role of both intrinsic factors and environmental conditions in determining pH stability and microbiological quality in dairy products during storage (Deshwal *et al.*, 2023; Tan *et al.*, 2022).

Current results indicate that polylactic acid film coated with a silicon oxide layer provides an effective barrier against moisture loss. Of these biodegradable packages, polylactic acid film coated with a silicon oxide layer showed the best results in moisture content, pH, microbiological stability, and water activity tests, indicating superior preservation capabilities for dairy products. The original packaging demonstrated optimal results in microbiological and moisture retention tests. Therefore, it is important to further improve biodegradable packaging, including the polylactic acid coated with a silicon oxide layer, until complete product protection is achieved.

Polylactic acid film coated with silicon oxide emerged as a preferred choice for dairy packaging due to its higher barrier efficiency properties against oxygen, moisture, and light, which help preserve shelf life and the quality of dairy products more effectively than standard polylactic acid alone. This combination of biodegradability and enhanced performance makes it a sustainable yet practical solution for dairy packaging. The silicon oxide provides protection against UV light, which can degrade certain nutrients in dairy products, such as vitamins, and cause undesirable flavour changes. The silicon oxide layer serves as a protective barrier, especially effective for preserving light-sensitive products such as sour cream and yoghurt. Additionally, the silicon oxide-coated polylactic acid film has reduced gas permeability, making it more effective at preventing off-flavours and odours from impacting the dairy product, thereby helping to maintain its original flavour and freshness (Zhang *et al*., 2023). Also developing biodegradable polyolefin shrink films for dairy products, mainly cheese, is a promising approach to reducing environmental impact while preserving the functional properties required for food packaging. Polyolefin films, widely used in the industry of packaging, can be modified to enhance biodegradability without compromising their mechanical properties. This is achieved by incorporating specific catalysts and photoinitiators that facilitate the degradation of polymer chains into environmentally benign end-products, such as CO_2 and water (Wang & Yin, 2017). Additionally, blending polyolefins with biodegradable polymers, such as poly(butylene-adipate-co-terephthalate) and polylactic acid, can enhance biodegradability while maintaining the necessary shrinkability and transparency for packaging applications (Pietrosanto *et al*., 2022).

Given the diverse needs of dairy products, such as moisture control for semi-hard cheeses and strong oxygen and light barriers for yoghurt, silicon oxide-coated polylactic acid film provides the versatility needed to address these challenges. It becomes a suitable choice across a range of dairy products. While standard polylactic acid containers may work for yoghurt and semi-hard cheese in the short term, the added protection of the silicon oxide coating makes it the most versatile and effective option overall. Although this packaging demonstrated superior results, it is important to note that it is not edible, but solely biodegradable. Additional improvements should be considered to ensure adequate product protection. Research by Prajapati *et al*. (2023) has shown that active edible coatings containing antimicrobial agents, such as copper nanoparticles, have been optimised for application in soft cheeses like Paneer**.** These coatings help retain moisture, maintain optimal pH, and significantly reduce microbial proliferation (Prajapati *et al*., 2023). Such coatings could be a viable option for cottage cheese as well, offering an additional layer of protection against spoilage (Prajapati *et al*., 2023). Further in-depth research is needed to find optimised solutions for biodegradable packaging materials for dairy products.

Conclusions

Edible, natural, and compostable packaging film coatings represent a frontier of innovation in cheese packaging technology. Although several edible films have been developed by scientists, their application in cheese packaging has been limited due to small-scale tests. To fully assess the storage quality of cheese packaged in edible biodegradable films, further in-depth experiments are essential. Exploring multiple edible film coatings may be necessary to ensure the optimal quality and safety of cheese during storage. Looking ahead, there is significant potential for future research in the field of sustainable cheese packaging. Extensive testing of various edible and biodegradable materials holds the potential to preserve cheese quality and safety while advancing eco-friendly packaging solutions. However, while edible films show promise for cheese, their application to other dairy products remains challenging due to differences in consistency and composition. As such, research should focus on advancing biodegradable packaging materials that are versatile enough to meet the requirements of a range of dairy products. Although biodegradable coatings offer exciting prospects for enhancing the sustainability and functionality of dairy product packaging, significant knowledge gaps remain regarding their effects on product quality and safety during storage. By prioritising research in this area and fostering interdisciplinary collaboration, we can fully harness the potential of biodegradable coatings for dairy product packaging, paving the way for a more sustainable future in the dairy industry.

References

Aleksandrovas, E., Vasiliauskaitė, A., Milerienė, J., Muizniece-Brasava, S., Ciprovica, I., Songisepp, E., Rud, I., Axelsson, L., Kasparavičienė, B., Lutter, L., Malakauskas, M., & Šernienė, L. (2024). The Study of Combination of Biodegradable Packaging and Biocoating with Lactic Acid Bacteria as a Green Alternative for Traditional Packaging in Gouda Cheese. *Coatings*, 14, 886. DOI: 10.3390/coatings14070886

Artiga-Artigas, M., Acevedo-Fani, A., & Martín-Belloso, O. (2017). Improving the shelf life of low-fat cut cheese using nanoemulsion-based edible coatings containing oregano essential oil and mandarin fiber. *Food Control*, 76, 1–12. DOI: 10.1016/j.foodcont.2017.01.001

Ahmed, I., Zulfiqar, H., Hussain, I., Waqas, M., Farooq, M. F., & Zulfiqar, H. (2024). Green Biopolymers in Sustainable Packaging. *In Green Biopolymers for Packaging Applications*. CRC Press.161–192. DOI: 10.1201/9781003455356-7

Aziz, M. S. A., Salama, H. E., & Sabaa, M. W. (2018). Biobased alginate/castor oil edible films for active food packaging. *Lebensmittel-Wissenschaft und -Technologie*, 96, 455–460. DOI: 10.1016/j.lwt.2018.05.049

Basheer, V. A., & Muthusamy, S. (2022). Mathematical modeling and kinetic behavior of Indian Umblachery cow butter and its nutritional degradation analysis under modified atmospheric packaging technique. *Journal of Food Process Engineering*. DOI: 10.1111/jfpe.14042

Brandielli, M. C., Fonseca-Burgardt, V. C., Hashimoto, E. H., Tonial, I. B., Zemiani, A., Silva, A. F., Oro, S. R., Marchi, J. F., Badaró, A. C. L., Castro-Cislaghi, F. P., & Machado-Lunkes, A. (2020). Physicochemical parameters and lactic acid bacteria count during ripening of Brazilian regional cheese manufactured with the addition of autochthonous cultures. *Food Science and Technology International*, 40(4), DOI: 10.1590/FST.23219

Cammarelle, A., Viscecchia, R., & Bimbo, F. (2021) Intention to Purchase Milk Packaged in Biodegradable Packaging: Evidence from Italian Consumers. *Foods.* 10(9), 2068. DOI: 10.3390/foods10092068

Cao-Hoang, L., Chaine, A., Grégoire, L., & Waché, Y. (2010). Potential of nisin-incorporated sodium caseinate films to control Listeria in artificially contaminated cheese. *Food Microbiology*, 27(7), 940–944. DOI: 10.1016/j.fm.2010.05.025

Ceylan, H. G., & Atasoy, A. F. (2022). Optimization and characterization of prebiotic concentration of edible films containing Bifidobacterium animalis subsp. lactis BB-12® and its application to block-type processed cheese. *International Dairy Journal*, 134, 105443. DOI: 10.1016/j.idairyj.2022.105443

Chen, H., Wang, J., Cheng, Y., Wang, C., Liu, H., Bian, H., Pan, Y., Sun, J., & Han, W. (2019). Application of protein-based films and coatings for food packaging: A review. *Polymers*, 11(12), 2039. DOI: 10.3390/polym11122039

Coimbra, P., Marona, B., Henriques, M. H. F., Campos, L., Gomes, D. M. G. S., Vitorino, C., Sousa, J. J. S., Braga, M. E. M., & Gaspar, M. C. (2023). Edible films based on potato and quince peels with potential for the preservation of cured cheese. *Food Packaging and Shelf Life*, 40, 101176. DOI: 10.1016/j.fpsl.2023.101176

Costa, M. J., Maciel, L. C., Teixeira, J. A., Vicente, A. A., & Cerqueira, M. A. (2018). Use of edible films and coatings in cheese preservation: Opportunities and challenges. *Food Research International*, 107, 84–92. DOI: 10.1016/j.foodres.2018.02.013

Cui, H. Y., Wu, J., Li, C. Z., & Lin, L. (2016). Anti-listeria effects of chitosan-coated nisin-silica liposome on Cheddar cheese. *Journal of Dairy Science*, 99(11), 8598–8606. DOI: 10.3168/jds.2016-11658.

Deshwal, G. K., Tiwari, S., Kumar, A., Raman, R., Kadyan, S. (2021). Review on factors affecting and control of post-acidification in yoghurt and related products. Trends in Food Science and Technology, 109, 499–512. DOI: 10.1016/J.TIFS.2021.01.057

Di Pierro, P., Sorrentino, A., Mariniello, L., Giosafatto, C. V. L., & Porta, R. (2011). Chitosan/whey protein film as active coating to extend Ricotta cheese shelf-life. LWT - *Food Science and Technology*, 44(10), 2324–2327. DOI: 10.1016/j.lwt.2010.11.031

Dinika, I., Pratap-Singh, A., Frisullo, P., & Saldaña, M. D. A. (2020). Potential of cheese whey bioactive proteins and peptides in the development of antimicrobial edible film composite: A review of recent trends. *Trends in Food Science and Technology*, 103, 57–67. DOI: 10.1016/j.tifs.2020.06.017

Dukalska, L., Ungure, E., Augspole, I., Muizniece-Brasava, S., Levkane, V., Rakcejeva, T., & Krasnova, I. (2013). Evaluation of the influence of various biodegradable packaging materials on the quality and shelf life of different food products. *Rural Sustainability Research*, 30(1), 20–34. DOI: 10.2478/plua-2013-0011

El-Safety, S. F., Abbas, D., Nasef, R., & Khalil, R. (2017). Changes in the Quality and Oxidation Indices of Cow's and Buffalo's Butter During Cold Storage. International Journal of Dairy Science, 5(1), 1–7. DOI: 10.21608/IJDS.2017.8069

El-Sayed, H. S., El-Sayed, S. M., Mabrouk, A. M. M., & Mohamed, S. A. (2021). Development of eco-friendly probiotic edible coatings based on chitosan, alginate, and carboxymethyl cellulose for improving the shelf life of UF soft cheese. *Journal of Polymers and the Environment*, 29, 1941–1953. DOI: 10.1007/s10924-020-02003-3

El-Sayed, S. M., & Youssef, A. M. (2024). Emergence of cheese packaging by edible coatings for enhancing its shelf-life. *Food Measurement and Characterization*, 18, 5265–5280. DOI: 10.1007/s11694-024-02564-0

Erceg, T., Šovljanski, O., Tomić, A., Aćimović, M., Stupar, A., & Baloš, S. (2024). Comparison of the properties of pullulan-based active edible coatings implemented for improving sliced cheese shelf life. *Polymers*, 16(2), 178. DOI: 10.3390/polym16020178.

EuroStat. (2023). Packaging waste statistics. Retrieved September 20, 2024, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics

Galus, S., & Kadzińska, J. (2015). Food applications of emulsion-based edible films and coatings. Trends in *Food Science & Technology*, 45(2), 273–283. DOI: 10.1016/j.tifs.2015.07.011

Goksen, G., Fabra, M. J., Ekiz, H. I., & López-Rubio, A. (2020). Phytochemical-loaded electrospun nanofibers as novel active edible films: Characterization and antibacterial efficiency in cheese slices. *Food Control*, 112, 107133. DOI: 10.1016/j.foodcont.2020.107133

Han, J. W., Ruiz-Garcia, L., Qian, J. P., & Yang, X. T. (2018). Food packaging: A comprehensive review and future trends. *Comprehensive Reviews in Food Science and Food Safety*, 17(4), 860–877. DOI: 10.1111/1541-4337.12343

Holm, V. K., Mortensen, G., Vishart, M., & Petersen, M. A. (2006). Impact of poly-lactic acid packaging material on semi-hard cheese. *International Dairy Journal*, 16(8), 931–939. DOI: 10.1016/j.idairyj.2005.09.001

Yaashikaa, P. R., Kamalesh, R., Kumar, P. S., Saravanan, A., Vijayasri, K., & Rangasamy, G. (2023). Recent advances in edible coatings and their application in food packaging. *Food Research International*, 173(Part 2), 113366. DOI: 10.1016/j.foodres.2023.113366

Jouki, M., Yazdi, F. T., Mortazavi, S. A., & Koocheki, A. (2013). Quince seed mucilage films incorporated with oregano essential oil: Physical, thermal, barrier, antioxidant and antibacterial properties. *Food Hydrocolloids*, 36, 9–19. DOI: 10.1016/j.foodhyd.2013.08.030

Jurić, M., Maslov Bandić, L., Carullo, D., & Jurić, S. (2024). Technological advancements in edible coatings: Emerging trends and applications in sustainable food preservation. *Food Bioscience*, 58, 103835. DOI: 10.1016/j.fbio.2024.103835

Koukoumaki, D. I., Papanikolaou, S., Ioannou, Z., Gkatzionis, K., & Sarris, D. (2024). The development of novel edible films from single-cell protein produced by the biotechnological valorization of cheese whey. *Applied Microbiology*, 4(3), 1030–1041. DOI: 10.3390/applmicrobiol4030070

Kouser, F., Kumar, S., Bhat, H. F., Noor, S., Manzoor, M., Dar, B. N., Hassoun, A., Aït-Kaddour, A., Shabbir, M. A., Aadil, R. M., & Bhat, Z. F. (2023). Effectiveness of Terminalia bellerica-based bioactive edible film in controlling the microbial growth and lipid oxidation of cheese during storage. *Food Chemistry Advances*, 2, 100213. DOI: 10.1016/j.focha.2023.100213

Kumari, M., Mahajan, H., Joshi, R., & Gupta, M. (2017). Development and structural characterization of edible films for improving fruit quality. Food Packaging and Shelf Life, 12, 42–50. DOI: 10.1016/j.fpsl.2017.02.003

Lappa, I. K., Papadaki, A., Kachrimanidou, V., Terpou, A., Koulougliotis, D., Eriotou, E., & Kopsahelis, N. (2019). Cheese whey processing: Integrated biorefinery concepts and emerging food applications. *Foods*, 8(8), 347. DOI: 10.3390/foods8080347.

Lopes, J., Pettersen, M. K., Grøvlen, M. S., Sharmin, N., Li, D., Wetterhus, E., Ferreira, P., Coimbra, M. A., & Goncalves, I. (2024). Heat-sealable bioplastic films of blended locust bean and potato byproducts for active packaging of fatty foods: Cheese and oat cookies as case studies. *Food Hydrocolloids*, 147, 109322. DOI: 10.1016/j.foodhyd.2023.109322.

Makhal, S., Kanawjia, S. K., & Giri, A. (2015). Effect of microGARD on keeping quality of direct acidified Cottage cheese. Journal of Food Science and Technology-Mysore, 52(2), 936–943. DOI: 10.1007/S13197-013-1055-2

Marcet, I., & Álvarez, C. (2023). The characterization of biodegradable films and food packaging. *Membranes*, 13(10), 826. DOI: 10.3390/membranes13100826

Muizniece-Brasava, S., Kirse-Ozolina, A. (2018). Attitudes of Latvian consumers to traditional and eco-friendly food packaging materials: comparison of 2007 and 2017. 17th International Scientific Conference "*Engineering for Rural Development*". Jelgava, Latvia. DOI:10.22616/ERDev2018.17.N560.

Musiy, L., Tsisaryk, O., Slyvka, I. Mykhaylytska, O., & Gutyj, B. (2017). Study of keeping probiotic properties of sour-cream butter at storage. ScienceRise: Biological Science, 2, 27–33. DOI: 10.21303/2504-5695.2017.00318

Nekera, K. D., Kuyu, C. G., Tola, Y. B., & Gemechu, A. T. (2023). Chemical, microbial, and sensory characteristics of cow butter as affected by modified atmospheric packaging. Journal of Agriculture and Food Research, 14, 100892. DOI: 10.1016/j.jafr.2023.100892

Patel, H. G., Modha, M. H., & Ranganadham, M. (2017). Packaging of Dairy Products. New Delhi, India: Indian Council of Agricultural Research.

Patel, R., Prajapati, J. P., & Balakrishnan, S. (2018). Packaging trends of dairy and food products. Research and Reviews: *Journal of Food and Dairy Technology*, 6(1), 1–9. e-ISSN:2321-6204

Pietrosanto, A., Apicella, A., Scarfato, P., Incarnato, L., & Di Maio, L. (2022). Development of novel blown shrink films from poly(lactide)/poly(butylene-adipate-co-terephthalate) blends for sustainable food packaging applications. *Polymers*, 14(14), 2759. DOI: 10.3390/polym14142759

Pluta-Kubica, A., Jamróz, E., Kawecka, A., Juszczak, L., & Krzyściak, P. (2020). Active edible furcellaran/whey protein films with yerba mate and white tea extracts: Preparation, characterization and its application to fresh soft rennet-curd cheese. *International Journal of Biological Macromolecules*, 155, 1307–1316. DOI: 10.1016/j.ijbiomac.2019.11.102.

Prajapati, P., Garg, M., Akhtar, S., Ansari, T. M., Chopra, R. N., Anand, S., & Sadhu, S. D. (2023). Development and optimization of active edible coatings to improve the shelf life of Indian soft cheese. *Research Square*. DOI: 10.21203/rs.3.rs-3176359/v1

Ramos, O. L., Pereira, J., Silva, S. I., Fernandes, J. C., Franco, M., Lopes-da-Silva, J., & Vicente, A. (2012). Evaluation of antimicrobial edible coatings from a whey protein isolate base to improve the shelf life of cheese. *Journal of Dairy Science*, 95(11), 6282–6292. DOI: 10.3168/jds.2012-5478

Rawdkuen, S. (2019). Edible films incorporated with active compounds: Their properties and application. In Active Antimicrobial Food Packaging. *IntechOpen*. DOI: 10.5772/intechopen.80707

Rejeesh, C. R., & Anto, T. (2023). Packaging of milk and dairy products: Approaches to sustainable packaging. Materials Today: *Proceedings*, 72, 2946–2951. DOI: 10.1016/j.matpr.2022.07.467

Saez-Orviz, S., Marcet, I., Rendueles, M., & Díaz, M. (2022). Preparation of edible films with Lactobacillus plantarum and lactobionic acid produced by sweet whey fermentation. *Membranes*, 12(2), 115. DOI: 10.3390/membranes12020115

Sanyang, M. L., Sapuan, S. M., Jawaid, M., Ishak, M. R., & Sahari, J. (2015). Effect of plasticizer type and concentration on tensile, thermal, and barrier properties of biodegradable films based on sugar palm (Arenga pinnata) starch. *Polymers*, 7, 1106–1124. DOI: 10.3390/polym7061106.

Talha, M., Arif, S., Khan, M. K. I., & Maan, A. A. (2024). Intelligent packaging of dairy products. In S. P. Bangar & M. Trif (Eds.), Developments in Food Quality and Safety: *Intelligent Packaging* (pp. 217–250). Academic Press. DOI: 10.1016/B978-0-443-15388-4.00009-2

Talwalkar, A., & Kailasapathy, K. (2004). A review of oxygen toxicity in probiotic yogurts: Influence on the survival of probiotic bacteria and protective techniques. *Comprehensive Reviews in Food Science and Food Safety*, 3(3), 117–124. DOI: 10.1111/j.1541-4337.2004.tb00061.x

Tan, D., Ma, A., Wang, S., Zhang, Q., Jia, M., Kamal-Eldin, A., Wu, H., & Chen, G. (2021). Effects of the oxygen content and light intensity on milk photooxidation using untargeted metabolomic analysis. Journal of Agricultural and Food Chemistry, 69(26), 7488–7497. DOI: 10.1021/acs.jafc.1c02823

Torrijos, R., Nazareth, T. M., Calpe, J., Quiles, J. M., Mañes, J., & Meca, G. (2022). Antifungal activity of natamycin and development of an edible film based on hydroxyethylcellulose to avoid Penicillium spp. growth on low-moisture mozzarella cheese. *LWT - Food Science and Technology*, 154, 112795. DOI: 10.1016/j.lwt.2021.112795.

Verbytskyi S., Muižniece-Brasava S., Minorova A., Patsera N., Kozachenko O., Nedorizaniuk L. (2024). Biodegradable food packaging: Institutional and social aspects. *Food Resources*, 12(23), 8–15. DOI:10.31073/foodresources2024-23-01

Verbytskyi, S., Kuts, O., Patsera, N., Kozachenko, O., & Muižniece-Brasava, S. (2023). Packaging of milk products: Possibility and expedience of using biodegradable polymers for the purpose. In Trends in Lean Food Production and Packaging: Proceedings of the 12th International Specialized Scientific and Practical Conference, September 20, 2023 (pp. 44–48). Kyiv, Ukraine: National University of Food Technologies

Vroman, I., & Tighzert, L. (2009). Biodegradable polymers. *Materials*, 2(2), 307–344. DOI: 10.3390/ma2020307

Wagh, Y., Pushpadass, H. A., Emerald, F. M. E., & Nath, B. S. (2014). Preparation and characterization of milk protein films and their application for packaging of Cheddar cheese. *Journal of Food Science and Technology*, 51(12), 3767–3775. DOI: 10.1007/s13197-012-0916-4

Wang, S., Li, C., Copeland, L., Niu, Q., & Wang, S. (2015). Starch retrogradation: A comprehensive review. *Comprehensive Reviews in Food Science and Food Safety*, 14(5), 568–585. DOI: 10.1111/1541-4337.12143

Wang, Z., & Yin, Q. (2017). Degradable polyolefin heat-shrinkable film material and preparation method thereof. Patent No. CN106519400A. China National Intellectual Property Administration.

Zambujal-Oliveira, J., & Fernandes, C. (2024). The contribution of sustainable packaging to the circular food supply chain. *Packaging Technology and Science*, 37(5), 443–456. DOI: 10.1002/pts.2802

Zhang, H., & Sablani, S. S. (2021). Biodegradable packaging reinforced with plant-based food waste and by-products. *Current Opinion in Food Science*, 42, 61–68. DOI: 10.1016/j.cofs.2021.05.003

Zhang, W., Ahari, H., Zhang, Z., & Jafari, S. M. (2023). Role of silica (SiO_2) nano/micro-particles in the functionality of degradable packaging films/coatings and their application in food preservation. Trends in Food Science & Technology, 133, 75–86. DOI: 10.1016/j.tifs.2023.01.009

Zhang, X., Zheng, Y., Zhou, C., Cao, J., Zhang, Y., Wu, Z., Pan, D., Cai, Z., & Xia, Q. (2024). Enhancing antioxidant capacity and controlling post-acidification potential in yogurt fermentation: A novel approach using thermosonication microstress and pineapple peel extracts. *Ultrasonics Sonochemistry*. DOI: 10.2139/ssrn.4723810

Zhong, Y., Cavender, G., & Zhao, Y. (2014). Investigation of different coating application methods on the performance of edible coatings on Mozzarella cheese. *LWT - Food Science and Technology*, 56, 1–8. DOI: 10.1016/j.lwt.2013.11.006.

Acknowledgement

Research was supported by the Latvian and Ukrainian Joint Scientific and Technological Cooperation Project "Enhanced use of environment-friendly biodegradable packages for dairy products (BIOPACK Dairy)" project N° ZV94 and to be fulfilled by the researchers of the Latvia University of Life Sciences and Technologies (Jelgava, Latvia) and Institute of Food Resources of NAAS (Kyiv, Ukraine).