UDC 60(519.5):339.1+615.4 https://doi.org/10.15407/biotech19.05.005

DEVELOPMENT AND OPTIMIZATION OF CHEESE BIOTECHNOLOGY WITH ADDITIVES

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The study presents a systematic analysis of strategies to develop global and domestic cheese markets, with a focus on implementing biotechnological innovations. The feasibility of using the optimal ratio of lactic acid starter cultures and rennet or phytoenzymes and phytoadditives or biopreservatives for the development of fermented and brine cheeses within the framework of the "K-Health" model, with an emphasis on individualized nutrition through functional fermentation in the context of harmonizing domestic technologies with international safety standards (ISO 22000:2018, Codex Alimentarius), is substantiated.

Aim. To assess the domestic cheese market and investigate the biotechnological process parameters (sourdough composition, fermentation temperature, and coagulation methods) on the structural and mechanical properties, microbial stability, and safety profiles of brine-ripened (such as brynza) and fermented milk cheeses, as well as with phytoadditives and biopreservatives in accordance with biosafety standards for the harmonization of technological cycles of cheese production

Materials and Methods. A methodological analysis of scientific literature and regulatory databases from PubMed, Scopus, Web of Science, and Google Scholar was conducted, focusing on the integration of starter cultures, protective cultures, phytoenzymes, and biopreservatives into the cheese-production bioindustry.

Results. The review demonstrates the dynamic nature of biotechnological implementations and the effectiveness of alternative components, including phytoenzymes, in cheesemaking. The concept of "Double Barrier" is proposed, based on a synergistic combination of a biopreservative (nisin) and a prebiotic phytoadditive (fenugreek), which ensures microbiological purity of the protein matrix, increases antioxidant stability, and strengthens the antimicrobial barrier. complementing the unique "K-Health" health model. In particular, for brine-ripened cheeses, the preliminary addition of a phytoextract, combined with prolonged ripening, optimizes flavor distribution and matrix stability. Based on the analysis, the need to create combined systems was identified.

Conclusions. The integration of microbial and plant agents into the biotechnology of fermented cheeses, within the framework of the "Double Barrier" concept, provides a scientific basis for functional cheesemaking. It allows minimizing the risks of microbial contamination during the ripening and storage stages, ensuring compliance with the requirements of the global safety standards ISO 22000:2018 and Codex Alimentarius without the use of synthetic additives, harmonizing modern food biotechnology with the principles of "Clean Label" and "Green Deal".

Keywords: food bioindustry, fermented milk and cheeses, brine-ripened cheese, functional product, lactic acid bacteria, enzymatic coagulation, phyto-enzymes, phyto-additives, nisin, biosafety.

Citation: Shved, O. V., Hubrii, Z. V., Vichko, O. I., Lisovska, T. (2026). Development and optimization of cheese biotechnology With additives. A review. *Biotechnologia Acta*, 19(5), 5–29. https://doi.org/10.15407/biotech19.05.005

The analysis of this work concerns well-known areas of research on the development of new and improvement of existing technologies aimed at improving the quality, diversifying the taste range, and providing preventive properties to food products, in particular fermented dairy products, for the creation of which starter cultures are functionally necessary for determining the safety of a bioproduct. There are about 200 milk processing enterprises in Ukraine. However, according to the marketing research of the domestic market of fermented milk products by Pro-Consulting, cheeses are mainly imported, in particular from producers of authentic cheeses in European countries (the Netherlands, Switzerland, Denmark, France, Italy and Spain), therefore the development of cheese biotechnology is relevant in Ukraine in relation to the requirements of the world market, strategic opportunities, international cooperation and harmonization of standards [1–3].

The main suppliers of dairy products to the Ukrainian market are Poland (43.8%), Germany (15.9%), the Netherlands (7.9%), France, Italy, and Belgium [4]. Cheese production has become a focus of innovation in the food bioindustry. It is a relevant segment in the fermented milk products market, as evidenced by the comparative characteristics of these products, which inform improvements to the target product. It also provides prospects for the development of production in Ukraine. In the current context of food biosafety challenges, Ukraine and the world need an expert approach to the use of protective methods and alternative options for the environmental and food sectors, based on adopted declarations, recommendations, laws, and quality standards for food production. The evolution of the market indicates a transition from small-scale local production to larger commercial operations of the modern diversified cheese market.

Analytical monitoring of production technologies and market filling assortment [5,6], determined by the qualitative completeness of the manufacturers' portfolio, the environmental safety of enterprises and the results of product quality and safety inspections for consumers in accordance with international standards, such as the ISO Food Safety Management System (International Standard ISO 22000:2018), as well as BRCGS food safety standards and BRCGS packaging standards ("BRC Global Standard — Food", 2008). Food safety is assessed by the absence of danger from consuming products (foodborne and infectious poisoning) and the subsequent impact on changes in metabolism or the state of the body (oncogenesis, mutagenesis, toxicoses, teratogenesis, hereditary genetic damage). Various programs are being developed that also stimulate environmental protection and the safety of growing agricultural raw materials and processing waste and wastewater, in particular, the European Green Deal (2019), the introduction of the EU Green Week (2021), and the International Green Week in Berlin (2026), which covers agro-industrial issues. combating environmental pollution with plastic packaging materials, "Plastic challenge" (2020), etc. Preparing Ukrainian goods for the market of European countries involves the need to meet the relevant safety requirements established in European directives and standards, as well as the need to perform correct marking (CE mark) and declaration of conformity to obtain a European Certificate of Conformity (Conformité Européenne) — a mark that certifies the product's compliance with the basic requirements of EU directives on safety, health and the environment, which in most cases are voluntary, but necessary for the effective sale of a food product, which also requires testing in specialized laboratories for compliance with safety requirementsIn case of non-compliance, to counter possible counterfeiting, the defective product is entered into the European Rapid Alert System for Dangerous Non-Food Products RAPEX (Rapid Exchange of Information System), now known as the Safety Gate alert, and the product is withdrawn from the market (food fraud in EU terminology — Food fraud — a wide range of illegal actions against food products related to nutritional impoverishment of products, contamination with chemicals or microbial contamination of products). As a result, the Global Food Safety Initiative (GFSI, Belgium, 2000) has developed a set of requirements for preventing counterfeiting and for food producers since 2016. 12 certification schemes have been recognized — the initiative's credo is "Once certified — accepted everywhere". In Ukraine, together with GFSI and Metro Cash&Carry, the International Finance Corporation (IFC) launched the "Food Safety in Ukraine" project, under which the 1st International Food Safety Forum was held in 2011. The Food Safety Forum focused on the implementation of HACCP systems (Hazard Analysis and Critical Control Points), which include risk analysis, critical control points at

all stages (production, storage, sales), disease prevention and ensuring a food safety culture (values and norms of behavior) to comply with international standards, through control of the entire production chain and improve public health through healthy nutrition, ensuring the body's needs for nutrients and through disease prevention [7].

International food safety forums, including the International Forum for Food Industry and Packaging (IFFIP) in Kyiv (2026), aim to improve food safety systems within enterprises, particularly among cheese producers, and to ensure public support for risk management. Ukrainian food producers receive support in their activities and entry into international markets, as well as in the implementation of the latest quality standards from the U-Food Association, and use the name "sour milk cheese", which meets Ukrainian standards and international terminology [8].

Leading agencies that forecast global agricultural markets, the United States Department of Agriculture (USDA) and the Organization for Economic Cooperation and Development (OECD), expect cheese production to increase. According to OECD estimates, more than 20 million tons of more than 2,000 varieties of cheese are produced annually in almost 130 countries and regions worldwide, of which about 500 are particularly famous. According to OECD estimates, in 2017–2019, annual global production averaged 23.6 million tons; in 2020, it was about 24.1 million tons.

Fermented dairy products, characterized by innovative applications in the food industry, are highly relevant to the food market. In the 2020 dairy production structure in Ukraine, according to marketing research by Pro-Consulting, the factors influencing, problems, and trends in the development of the dairy market in Ukraine were identified and investigated; in particular, fermented milk products accounted for 20.4%, and cheeses for 9.4%. The cheese market was characterized by mixed trends: production volumes of fresh cheeses from fermented milk continued to grow in 2021 (+7.4%), while production volumes of fermented cheeses continued to decline in 2021 (–14.2% compared to 2020). The war in the Middle East and Iran's logistical problems opened up opportunities for Ukraine to return to traditional export markets. The growth of raw milk production and weak domestic demand are forcing processors to focus more actively on exports. Leading agencies that forecast global agricultural markets, the United States Department of Agriculture (USDA) and the Organization for Economic Cooperation and Development (OECD), expect cheese production to increase. According to OECD estimates, more than 20 million tons of more than 2,000 varieties of cheese are produced annually in almost 130 countries and regions worldwide, of which about 500 are particularly famous. According to OECD estimates, in 2017–2019, annual global production averaged 23.6 million tons; in 2020, it was about 24.1 million tons.

The results of the 2023 auctions indicate that the imbalance between demand and supply for dairy products continues in Europe. The average price for dairy products decreased by 1.5% to $3,414 per ton. During the auction, the price index increased only for two products: butter and cheddar cheese. Butter rose by 3.8% to $4,922 per ton, and cheddar cheese by 1.5% to $5,086 per ton, but interest in these products began to decline due to oversupply in the European market. Dutch dairy producer Friesland Campina is optimizing butter production and has already closed its plants in Friesland and Rotterdam, sold its plant in China, and plans to develop the production of cream mixtures as an alternative product [9].

The war, of course, also affected the volume of cheese production in Ukraine. In 2022, the volume of fresh unfermented cheese production decreased by 29.5% compared to the pre-war year 2021. The volume of production of grated, powdered, blue, and other unprocessed cheeses in 2022 decreased by 22.6% compared to 2021. The volume of production of hard and semi-hard cheeses in 2022 decreased by only 11.8% compared to 2021. However, in 2024 alone, we observe an increase in the production of all types of cheeses, almost back to pre-war 2021 levels. In particular, the production of hard and semi-hard cheeses in 2024 increased by 20.4% compared to 2022 [10]. In January-August 2025, Ukraine produced 319 thousand tons of drinking milk, 226.9 thousand tons of fermented milk products, and 93.2 thousand tons of cheese. As experts predicted, the production of hard and semi-hard cheeses in 2025 will reach 62.8 thousand tons according to the State Statistics Service of Ukraine and the Ministry of Agrarian Policy and Food of Ukraine, compared to previous years [11]. In March 2026, Ukraine increased the natural volume of exports of milk and fermented milk products to 612 tons (+22%), whey to 1.71 thousand tons (+24%), and cheese to 1.32 thousand tons (+14%) compared to February of this year. [12].

Industry Perspectives. Socio-economic feasibility for domestic producers: Given the surplus in the European market and price fluctuations highlighted by agencies such as the OECD and the USDA, Ukrainian cheese producers are facing severe pressure. The financial feasibility of integrating starter cultures directly into the nisin and fenugreek vat solution is justified by the reduction in logistical losses. Although this formulation increases direct raw material costs by approximately 5–8%, it extends the shelf life of brine-ripened and fermented cheeses by 25–40%. In the context of the recent export growth observed in early 2026 (+14% in cheese export volumes), extending shelf life directly expands geographical logistical buffers. In addition, shifting the focus of production from commodity cheeses to specialized functional products reduces vulnerability to falling global dairy prices (e.g., a 1.5% decline to $3,414/ton at global auctions) by capturing highly profitable local and export niches. Innovative developments in the food bioindustry enrich the classic range of cheeses with complex microbial functional starter cultures, phytoenzymes, and bioadditives, complementing the unique K-Health model.

Materials and Methods

The analytical work employed methodological analysis and processing of literary data from online databases (PubMed, Scopus, Web of Science, Google Scholar) to assess the development of cheese biotechnology using starter cultures, protective cultures, coagulation enzymes, phytoadditives, biopreservatives, and food additives in the food bioindustry. The assessment structure took into account the technological parameters of biotechnology, portfolios on websites, and the harmonization of regulatory acts with international standards for both domestic and transnational producers, with a focus on the biotechnology of fermented milk and brine cheeses, as well as on food safety standards.

The mandatory complex of laboratory control of raw materials includes:

– Rennet-fermentation test (assessment of the technological suitability of milk microflora).

– Control of antibiotic residues (inhibitory substances that block the work of starter cultures).

– Determination of the number of somatic cells (an indicator of herd health and mastitis).

– Total bacterial inoculation (TBI).

Results and Discussion

Market need for cheese products. To analyze the development and optimization of biotechnology of some types of fermented cheeses with phytoadditives and biopreservatives, a systematic analysis of structural and functional characteristics and strategic priorities of the cheese market development was conducted, as well as an analysis of the modes of the main technological stages of production of various types of fermented cheeses. A comparative characteristic of microbial starter cultures and enzymes for the hydrolysis and coagulation of carbohydrates and milk proteins is presented, which are mainly related to the regulation of time and temperature parameters of fermentation and the selection of microbial producers of processes to improve the target product and the prospects for the development of production in Ukraine.

The production of fermented milk drinks and fermented cheeses, which appeal to consumers with their rich taste and aroma, is concentrated in European countries, particularly France, which produces over 400 different types of cheeses that hold a special place in French cuisine. Among domestic manufacturers with new engineering approaches for the sustainable development of the industry, experts note LLC “Milk House”, which was founded in 2002 and, since 2007, has belonged to the “Lactalis” group (Groupe Lactalis, France), which is one of the four leading dairy producers in the world and is a world leader in cheese production. Its products are sold in 170 countries worldwide. “Lactalis” has been successfully operating in the Ukrainian market since 1996, and its products are offered under the brands “President”, “Galbani”, “Dolce”, “Lactel”, “Lactonia”, “Fanni”, and “Loko Moko”. TM “Lactonia” is a line of specialized fermented milk products from LLC “Molochny Dim” (Ukraine), characterized by the use of yogurt starter and prebiotic lactulose to maintain intestinal health, designed for functional nutrition, helps normalize microflora, has a moderate fat content (1.5–2.2%), and is enriched with natural additives.

Ukrainian cheese producers face challenges in the modern market as European cheeses gain popularity, and according to forecasts from the Union of Dairy Enterprises of Ukraine (UDE), imports may exceed 50% by the spring of 2026. Thus, according to the UDE forecasts, disseminated in early 2026, the market

situation is critical. The share of imported cheeses in Ukraine in 2025 increased from 38% to 45% and continues to grow rapidly, and in March 2026, imports reached $32.5 million, significantly exceeding exports ($25.1 million) [13, 14]. According to cheesemakers, the most popular cheeses on the market today and those included in the TOP-10 cheese varieties in the world are mozzarella, emmental, parmesan, brie, cheddar, camembert, Gouda, peta, Swiss cheese, and gruyere [15].

According to the OECD, global production will increase to 26.8 million tonnes by 2029. The leading exporters of cheese are the European Union, New Zealand, and the United States. According to the OECD, they will account for about 65% of global cheese exports by 2029. The EU will remain the leading global exporter with a share of about 44% [16].

The global cheese market was valued at US$215.51 billion in 2025 and is expected to reach US$337.39 billion by 2033, growing at a CAGR of 5.8% from 2026 to 2033. The growth is explained by changing consumer tastes and preferences for a variety of exotic food flavors, increasing demand for plant-based cheese products, the introduction of new and unique cheese varieties, and the globalization of culinary trends [17], as shown in Fig. 1.

The cheese market includes fermented classic cheeses, which are classified by hardness into superhard, hard, semi-hard and soft, using starter microcultures (0.5–10%), which affect the reduction of milk acidity by converting lactose to lactic acid, accelerating syneresis (separation of whey), as well as the formation of the taste, aroma and pattern of the cheese during ripening, and with the subsequent introduction of an enzyme — rennet or microbial — with a standard strength of 860 IMCU/g (1.5–3 g of dry or 10-30 ml of liquid enzyme per 100 l of milk%) for coagulation, which is responsible for the coagulation of casein and the formation of cheese curd, as well as real processed and special cheeses, which differ in the type of microbiome of secondary ripening using lactic acid bacteria, propionic acid, blue and white mold and other types of cheese products, which differ in production technology and composition [18].

The ambassador of Ukrainian cheese culture, ProCheese expert, judge of the international cheese competition World Cheese Awards points to several classifications of cheeses — European (French — 7 categories: fresh, with washed rind, goat, with blooming (white) rind, blue, pressed, pressed-cooked; German — 5 categories: fresh, with white mold, with blue mold, sliced (Schnittk se), hard; and American classification. The classification closest to Ukrainian cheesemakers is the American classification, which divides cheeses into 8 categories according to the texture of the cheese dough: fresh cheeses; fresh-aged cheeses; cheeses with white mold; cheeses with washed rind; cheeses with blue mold; semi-hard cheeses; hard cheeses; flavored cheeses [19].

Fermentation technology is carried out using microbial producers of lactic acid (lactic acid bacteria), coagulation (plant and animal,

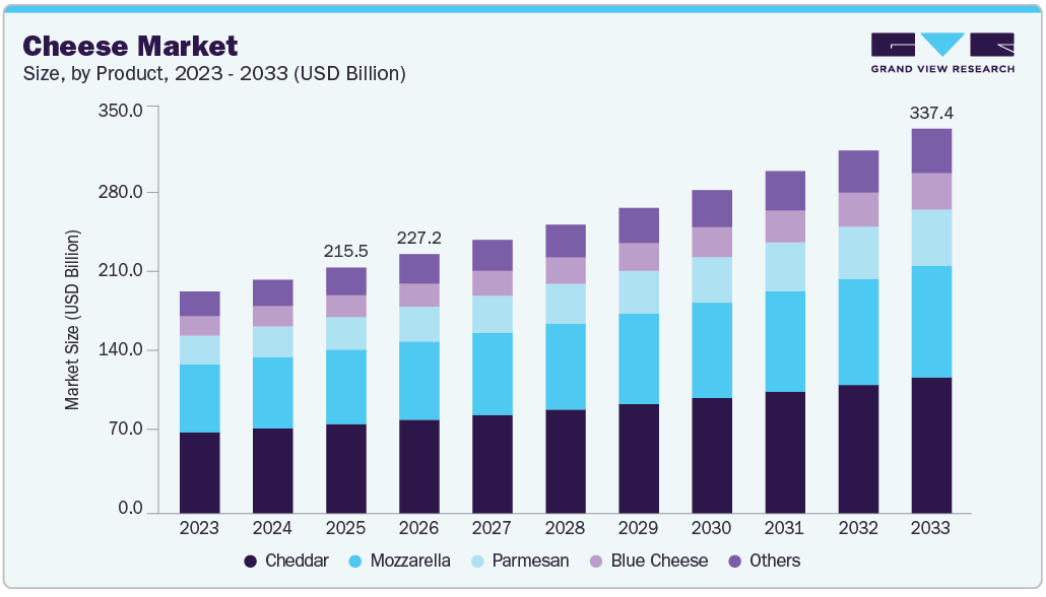


Fig. 1. **Structural dynamics and long-term forecast of the global cheese market through 2033**
Source: developed by the author based on Grand View Research reports, 2026–2033 [17].

particularly rennet, and microbial proteolytic enzymes), and solid-phase ripening (propionic bacteria, yeast, and fungi). Hard cheeses are also divided by the cooking temperature (second heating): high (thermophilic starter), medium (mixed starter), and low (mesophilic starter). It should be borne in mind that the optimal temperature for the enzyme to function is 32–36 °C, while low temperatures slow the process and high temperatures (above 40 °C) destroy the enzyme. Cheesemakers use mesophilic starters (low-temperature, 20–30 °C) for soft, semi-hard cheeses (such as Gouda) and thermophilic starters (high-temperature, over 40 °C) for hard cheeses (such as Parmesan, Emmental). As a result of a comprehensive study, we analyzed 73 types of hard and semi-hard cheeses: 35 recipes from the New England Cheesemaking Supply Company, authored by Jim Wallace; 30 processes for producing hard and semi-hard cheeses from the EU; and 8 technical specifications for hard cheeses from Ukrainian producers. It was found that the recipe for Ukrainian cheeses requires improvements and updates, innovative developments in fermentation technologies, new investments in engineering support for production, and the use of consulting recommendations for issuing certificates of conformity. Based on the analysis of the data obtained, it was established that the temperature of fermentation and coagulation is between 29 and 38 °C. The temperature of the second heating depends on the desired moisture content of the final product and the type of starter used, and ranges from 33 to 60 °C. The ripening period for European cheeses is at most 730 days, with an average of 223 days. In Ukrainian cheeses, ripening takes from 35 to 60 days. European cheese producers in the European Union most often choose mesophilic starter cultures — 53.3% of cases — and thermophilic and mixed starter cultures less often — 20% of the analyzed cheeses. Ukrainian producers use mesophilic starter cultures. A comparative study of the species composition of lactic acid bacteria in starter cultures used in recipes from the New England Cheesemaking Supply Company, authored by Jim Wallace, showed that the most frequently used mesophilic bacteria are *Lactococcus lactis* subsp. *lactis, Lactococcus lactis* subsp. *cremoris*, in 29/35 recipes of poured cheeses, as well as the thermophilic bacterium *Streptococcus thermophilus*, and other thermophilic bacteria, *Lactococcus lactis* subsp. *diacetylactis, Lactobacillus helveticus, Lactobacillus delbrueckii* subsp. *Lactis, Lactobacillus bulgaricus*, is less often used as an additional component of starter cultures and as a component of the secondary microbiome — the propionic acid bacterium *Propionibacterium freudenreichii* subsp. *shermanii*, yeast *Geotrichum candidum*, and brevibacteria *Brevibacterium linens, Trichothecium domesticum*. It has been established that the recipe of Ukrainian cheeses needs improvement and updating [20].

In Ukraine, the competitiveness of soft cheeses is a problem [21]. However, the nutritional value of cheeses is not inferior to that of hard rennet cheeses, but in recent years, there has been an increase in interest in soft rennet cheeses. Analysts explain the success of the fermented milk cheese product by several factors in modern food trends and images: rich in protein, relatively inexpensive, and versatile in use, an interesting component as a culinary designer and as a premium and even gastronomic product, which moves into the category of trendy products with high added value and great growth potential. Provided that current market trends and consumer needs are maintained, fermented milk cheese has every chance of long-term consolidation in its status as a functional product, one of the main favorites of healthy eating [22] (as shown in Table 1).

The development of biotechnology for soft fermented milk and brine cheeses is of practical interest for obtaining high-quality and safe, but more nutritious and sensory-appealing cheese using optimized technology, for expanding the range, replenishing commercial starters based on Ukrainian biovariants, and especially for enriching the beneficial properties of cheese, such as brynza, by introducing phytoadditives to the recipe. This is relevant both from a theoretical point of view and is practically attractive for updating traditional cheese-making recipes under industrial conditions and for obtaining the status of the European comprehensive PDO/PGI/TSG system for food products. Traditional products are characteristic of many countries. Some cheeses are protected by EU regulations; in particular, Commission Regulation (EU) No. 1151/2012 granted PDO/PGI registration for Parmigiano Reggiano (Parmesan) and Roquefort (Roquefort). Commission Regulation (EC) No. 642 of 2007 officially registered the name of the Polish cheese “Brynza Podhalańska” in the register of protected designations of origin (PDO), etc. [23].

Table 1

The main types and producers of brine cheeses that can be found in Ukraine

Type of cheese (according to classification)	Technological features and organoleptics	Composition of dominant microflora and enzymes	Main producers and TMs in Ukraine
Brine-ripened cheese (Carpathian brynza)	Cheese made from sheep's, goat's or cow's milk. Long-term maturation in brine. The consistency is tender and moderately dense	Mesophilic cultures: *Lactococcus* spp., *Lactobacillus* spp., and rennet (*chymosin*)	Yagotynska, Premialle, Ferma, Komo, Organic Milk, Tabakska
Pasta Filata type (Georgian sologuni)	Pulled cheese Characterized by the heat treatment of the cheese mass and its plasticization The structure is elastic and layered	Thermophilic cultures: *Streptococcus thermophilus*, *Lactobacillus* spp., *Leuconostoc*, and *Enterococcus*	Yagotynsky, Novgorod-Siversky, Sulugunko, Haisyn Milk Plant LLC Honest cheese
Soft pasta filata (Italian mozzarella)	Soft fresh cheese in the form of balls. delicate, High humidity, neutral milky taste. Sold in brine.	Lactic acid cultures: *Streptococcus thermophilus*, *L. helveticus* або *L. delbrueckii subsp. bulgaricus*	Yagotynska, Zotarella, Organic Milk, Silpo (import), Chesnyy syr
Soft acid-heat coagulated (Adyghe cheese)	Soft, unripened cheese with a delicate texture. Thermo-acid coagulation at 90–95 °C, Low salt content, pure sour milk taste) without preservatives, with optimal protein and amino acid composition	Residual thermophilic microflora (formed during the precipitation of proteins by whey).	Zlagoda, Ferma, Bratalivska cheese factory, Chesnyy cheese, farms
Feta type / Salad cheese (feta greek)	Cheese with a high salt content and a fragile structure is made using ultrafiltration technology.	Lactic acid cultures: *Lactobacillus delbrueckii* subsp. *bulgaricus*, *Streptococcus thermophilus*	Premialle, Komo, "Milk Line" LLC (TM Farm), Mevgal, Casa AzzurraFelata, Insalata, Auchan Salad Cheese

Source: author's development based on data from manufacturing companies.

As discussed back in September 2017 at a meeting of the working group on the development of regional and traditional food production, which became a kind of kick-off meeting for further work on creating a comprehensive PDO/PGI/TSG (Protected Designation of Origin/Protected Geographical Indication/Traditional Specialities Guaranteed) system for food products, similar to the European one, such developments are an increase in the marketing potential of domestic products and one of the possible growth points of the agricultural industry. The creation of food products and fermented milk cheeses with a protected designation of origin (PDO/PDO) or geographical indication (PGI/PGU) in the EU is based on unique regional characteristics, traditional production methods (specific technology), and strict adherence to specifications registered in the EU DOOR database (Database of Origin and Registration) — the official register of the European Commission. The registration process includes developing a detailed product specification, confirming its uniqueness (historical aspects and characteristics of the raw materials), and submitting an application to the European Commission through national authorities.

The main aspects of the creation of traditional cheeses are known to be:

– Protected Designation of Origin (PDO) or Protected Geographical Indication (PGI) — the product must be produced, processed, and prepared in a specific geographical area using recognized technologies. An example is the production of fermented-milk cheese using local starter cultures and milk.

– Specific Technology (TSG) — traditional guaranteed specificity, which focuses on a traditional composition or production method that distinguishes it from similar products.

An example is the use of specific bacteria, *Lactobacillus acidophilus* or *Lacticasebacillus casei*.

According to experts [24], such an approach is expected to protect economic interests and increase the marketing potential of Ukrainian food producers, especially small and medium-sized ones. It will also contribute to the development of regions with original products, driven by growing interest in agrotourism. France leads the European cheese market due to its rich cultural heritage, wide variety of cheeses, and high domestic and international demand.

Analysis of global forecasts (Fig. 1) indicates a stable expansion of the cheese market until 2033, with the specialty cheese and functional product segments occupying a special place. This correlates with our data (Table 1) on the potential of Ukrainian brine cheeses, which require biotechnological modernization to enter international markets. Ukraine also has many artisanal cheese factories (for example, Golytsia) that produce high-quality brynza and feta from goat and cow's milk.

Biotechnological integration. New premium products are emerging in the fresh-fermented milk cheese market. [25, 26]. Some well-known brand products are experimenting with fruit flavors, proving that cheese can be not only salty or neutral, but also a full-fledged dessert. For the preparation of high-quality classic fermented milk cheese (sour milk cheese), mesophilic or mesothermophilic starter cultures are used, which provide a delicate structure and a pleasant taste. [27].

The normal microflora of cheese starter includes *Lactococcus lactis subsp. cremoris, Lactococcus lactis subsp. lactis, Streptococcus thermophilus, Lactobacillus helveticus.*

STAETER starter for fermented cheese provides high acid production, aroma, and structure: *Lactococcus lactis* subsp. *lactis* — the main culture for acid production; *Lactococcus lactis* subsp. *cremoris* — responsible for texture and mild taste; *Lactococcus lactis* subsp. *lactis var. diacetylactis* — produces aromatic compounds; *Leuconostoc mesenteroides* subsp. *cremoris* — provides aroma and structure. For the preparation of craft fermented cheese, it is recommended to ferment milk with a starter culture such as Danisco (DuPont Nutrition & Health, France, professional) or Good Food (Ukraine, for home use) (0.15–0.2 g/10 l) (2–3 days) or kefir (one day) at a temperature of 25–32 °C. The product is ready in 10–12 hours. It is then heated over low heat or in a steam bath until the whey separates from the cheese. The cheese mass is strained through a gauze-lined sieve or colander to drain the liquid, and then cooled to obtain the finished product.

A wide range of domestic dry bacterial starter cultures Vivo and Good Food (Ukraine) allows you to prepare natural yogurts, kefir, fermented baked milk, sour cream, as well as fermented milk cheeses (bryzhak, cheese), contain live cultures, are suitable for children's and dietary nutrition, ensuring high quality of homemade dairy products, in particular, it includes a specialized starter culture "Sour Milk Cheese" (storage conditions and shelf life — 1–3 months at +4–8 °C, in the refrigerator; 1 year at –18 °C, in the freezer), which ensures the production of a useful product rich in calcium, protein and phosphorus, suitable for dietary and childrens nutrition.

Biotechnology (recipe) for rennet-crafted cheese of the brynza type involves coagulating milk with rennet enzyme: adding starter to milk at 32–35 °C, uniform mixing, and aging for 40–60 minutes at room temperature, thereby activating the dry starter of lactic acid bacteria. Composition of starter: *Lactococcus lactis subsp. lLactis; Lactococcus lactis subsp. cremoris; Lactococcus lactis subsp. lactis var. diacetylactis; Streptococcus thermophilus*. [28]. Therefore, to obtain Kraft cheese, rennet (or its plant/microbial substitute, the Meito enzyme from oat bran) is mixed at 35 °C until a single, jelly-like mass (milk curd) forms, which is then separated with a knife. The curd is cut into 10–15 mm cubes and left for 5 minutes to allow natural compaction. Then the curd mass is slowly heated for 10–20 minutes to 38 °C, after which a 1-minute holding period is carried out, the yellowish whey is separated, the curd is treated with salt 1–2 g/kg, the head is formed for 1 hour, 2–3 turnings are made with an interval of 30 minutes and the mass is ripened under weight for 12 hours at room temperature, the main holding period is in a 5–20% concentrated salt solution (1 kg for 6 hours), which ensures the formation of Kraft cheese.

Bacterial starters are the main products offered by well-known brands on the Ukrainian market for the preparation of cheeses and fermented milk products, as they provide high-quality fermentation and offer a wide range of bacteria, many of which are used as direct-injection starters without activation [29, 30]. The following starter cultures are used in the

biotechnology of fermented dairy products: *Lactobacillus bulgaricus, Lactobacillus acidophilus, Lactobacillus helveticum*, and others, which are functionally necessary components (specific physicochemical, dietary, therapeutic, prophylactic, and organoleptic properties).

The main starters produced (STARTER direct-injection DVS — Direct Vat Set — starters for fermented milk cheese) by well-known cheese-making brands are listed in Table 2. Taking into account the biochemistry of gas formation in cheeses, the starters were divided into two types: O-types (acid-only) and LD-types (acid + aroma).

Screening of the technological properties of natural strains of lactic acid bacteria allows identifying the main types of technological bacteria: [20]

– Mesophilic bacteria (at 25–30 °C): *Lactococcus lactis ssp. lactis* — produces lactic acid, forms the main texture; *Lactococcus lactis ssp. cremoris* — provides a delicate texture and aroma; *Leuconostoc* — aroma-forming bacteria that produce carbon dioxide and diacetyl (for cheeses with eyes, such as Gouda).

– Thermophilic bacteria (at 40–45 °C): *Streptococcus thermophilus* — rapid acidification, used for hard and semi-hard cheeses*; Lactobacillus helveticus* — provides a rich taste, actively breaks down proteins (proteolysis); *Lactobacillus delbrueckii subsp. lactis/bulgaricus* — for cheeses with a high second heating temperature.

Important starter cultures for improving the body are probiotic starter cultures based on *Bifidobacterium species, Bifidobacterium animalis, Bifidobacterium bifidum, Lactobacillus acidophilus, Lactobacillus bulgaricus, Lactobacillus fermentum, Lactobacillus plantarum, Lactobacillus rhamnosus, and Propionibacterium rendenreichii subsp. shermanii, Streptococcus thermophilus*. The results of studies on the technological properties of natural lactic acid bacteria (screening of 106 MKB cultures, in particular *Lactococcus lactis*, showed that it can be used as a technological bacterium [31–36]).

The use of probiotic cultures in the production of various functional dairy products confirms their potential in cheesemaking [37 Probiotic properties of fermentation compositions are transferred to food products, making probiotic additives the most prominent ingredient in the era of functional nutrition. Bacteria belonging to the genera *Pediococcus, Lactococcus, Enterococcus, Streptococcus, Propionibacterium*, and *Bacillus* are considered potential probiotic microbes [38, 39]. Probiotic action is exhibited by microorganisms of the genus *Enterococcus*, which are endowed with biochemical properties with the ability to synthesize biologically active substances, high antagonistic properties to opportunistic microflora, produce bacteriocins, and therefore are used as a leavening agent in the dairy industry in the production of soft fermented cheeses (brynza, cheddar, salami, etc.) [40].

The technology for the production of soft cheese with probiotic properties has been studied and scientifically substantiated, an innovative technology has been developed using starter compositions from bacterial concentrates of direct-added lacto- and bifidobacteria with high probiotic and proteolytic properties, as well as the composition of starter compositions for the production of soft probiotic cheeses using mixed cultures/monocultures of lactobacteria and monocultures of bifidobacteria adapted to milk, consisting of the following starter cultures: *FD DVS La5, FD DVS Bb-12, FD DVS CHN-19* and *FD DVS L. helveticus* in the presence of fructose as a bifidogenic factor [41]. The feasibility of high-temperature heat treatment of the normalized mixture has been demonstrated, and the mass fractions of milk-coagulating ingredients for producing soft cheeses with probiotic properties have been determined to increase cheese yield and obtain safe, high-biological-value products [42].

The method of producing soft cheese with probiotic properties includes ripening of the source milk, normalization, heating, purification, pasteurization, cooling to the fermentation temperature; adding a composition of fermentation cultures and a milk-clotting enzyme; mixing, removing whey, fermentation, salting and ripening of the cheese mass; after ripening, the milk is first heated, then purified and normalized; pasteurized normalized milk is cooled and ultrafiltered; the retentate, separated from the permeate, is heated and homogenized. Cheese preparation is distinguished by its unique microbial composition, which ensures a stable course of the technological process and high quality of the finished product. A protective culture is an effective means of neutralizing oil bacteria, eliminating cheese defects such as late swelling, activating the fermentation of raw materials, and reducing nitrite content. Fermentation cultures for traditional dairy products reproduce the composition and

Table 2

Basic starter cultures, produced by well-known brands, for cheese making

Technological group of starter cultures	Species composition of microorganisms	Functional role in biotechnology	Examples of commercial batches and manufacturers
Mesophilic homofermentative (O-types)	*Lactococcus lactis* subsp. *lactis;* *L. lactis* subsp. *cremoris*	Rapid acidification, formation of a dense clot (cottage cheese, fresh cheeses). Professional starters	**CHOOZIT MA 11** (Danisco, France); **R-704** (Chr. Hansen, Denmark); **M030** (Sacco, Italy); **Bioprox** серія DI-PROX (Bioprox Cultures, France)
Mesophilic heterofermentative (LD-types)	*Lb. lactis* subsp. *diacetylactis;* *Leuconostoc mesenteroides;* *Lactococcus lactis (*subsp. *lactis* + *cremoris* + var. *diacetylactis);* *Leuconostoc mesenteroides* subsp. *cremoris;* *Streptococcus thermophilus*	Aroma formation (CO_2, diacetyl), formation of buds and creamy taste.	**Flora Danica** (серії MA 11, MM 100); **CHN-11** (Chr. Hansen, Denmark); **MM 101** (Danisco, France)
Thermophilic	*Streptococcus thermophilus;* (to speed up fermentation) *Lactobacillus helveticus;* *Lb. bulgaricus*	High proteolytic activity, work at high temperatures (Suluguni, Mozzarella, Brynza)	**ST-020/ST022** (Sacco, Італія); **CHOOZIT TM** (Danisco, France); **ST 071, ST 073, ST 75, ST 077.** (Chr. Hansen, Denmark)
Meso-thermophilic (mixed)	Combinations *Streptococcus salivarius* ssp. *thermophilus,* *Leuconostoc mesenteroides*	Universal starters for process intensification and stable texture; Suitable for baby food for children (from 6 months).	**STM 211** (Alce, Italy); **NGLHF** (Alce, Italy); **Lyofast** (Sacco System, Italy); **MSY-Lactoferm** (Biocgem Lactoferm, Italy);
	Lactococcus lactis ssp. *lactis,* *Lactococcus lactis* ssp. *cremoris,* *Lactococcus lactis ssp. lactis biovar diacetylactis* *Lactobacillus acidophilus*		**VIVO Сир** (Ukraine)); **Good Food** №5 (Italy/ Ukraine)
Protective and probiotic	*Lactobacillus rhamnosus* (*Lacticaseibacillus rhamnosus)* *Lactobacillus plantarum*) *(Lactiplantibacillus plantarum)* (before *Propionibacterium*)	Inhibition of mold and yeast, biopreservation, and increase of biological value. Create a favorable environment for the growth of *bifido-* and *lactobacteria* (prebiotic effect).	**Holdbac** (Danisco France), **Protek/LP** (Lactoferm, Italy)
		domestic natural starter cultures for direct application, produced from natural strains without GMOs, lyophilized dry cultures with a high density of bacteria (up to 10^{10} CFU/g)	**Iprovit** (Ukraine)

Source: author's development based on data from manufacturing companies.

characteristic organoleptic indicators to the greatest extent, whereas for functional products, the main emphasis is on biological activity [43].

Under the action of the enzyme pepsin on milk peptides in an acidic environment, one of the most important antimicrobial peptides is formed, in particular, the lactoferrin fragment (lactoferricin) is resistant to high temperatures and exhibits antimicrobial activity in a wide range of pH values of the environment, and at relatively low concentrations, lactoferricin inhibits the development of many types of gram-negative (*E. coli, Salmonella spp., K. pneumoniae, Y. enterocolitica*) and gram-positive (*Bacillus spp., Clostridium spp., E. faecalis, Streptococcus spp.*) bacteria, yeast, fungi (*Aspergillus spp., Penicillium spp.*), and also has an inherent antiviral effect (on hepatitis *C viruses, herpes, adenoviruses*). At the same time, strains of lactic acid bacteria, in particular the species *Lc. Lactis* and *Lb. casei* are resistant to lactoferricin [34, 37].

Popularity among consumers and interest among scientists has also gained the preparation of cheese of the brynza type with the addition of special autochthonous strains of lactic acid bacteria *(LACB*) of the genera *Leuconostoc, Pediococcus, Propionibacterium, Aerococcus, Streptococcus, Enterococcus,* namely *Leuconostoc mesenteroides, Lactobacillus brevis, Lactobacillus lactis, Bifidobacterium bifidum*, which are actively used for the production of fermented food products, as additional in situ cultures to pasteurized milk for inoculation fermentation and coagulation of fermented milk liquid with a milk-enriching enzyme of a combined probiotic biological preparation [44, 45]. Scientists analyzed the production technologies of brine cheeses such as bryndza (DSTU 7565:2009). For the production of Budza and Carpathian bryndza, the coagulant "Glek" or a liquid milk coagulant with an extended shelf life was used [46].

Many Central European countries produce varieties of brynza. The cheese is known by different names in different countries: Bryndza Podhalańska in Poland [47], Bryndza in Slovakia [48], Brynza z burdufu in Romania [49], Tulum cheese in Turkey and Bulgaria [50, 51]. Enzymatic coagulation of milk (coagulation) is an important step in most cheese production processes. One of the main proteases responsible for this coagulation is chymosin (from the Greek chymos — juice), which is present in the rennet of ruminants and has been used in the dairy industry for centuries to produce various types of cheese [52]. Most of the industrial rennet powder of animal origin used in dairies comes from recombinant sources, while only 20–30% is of natural origin. To preserve the enzymatic properties of rennet, it must be stored at 4–6 °C. In fact, the specific and qualitative characteristics of cheeses are formed under the influence of biochemical processes driven by the cheese's microflora, as well as by the technological parameters and regimes of the stages of its production [53]. Biotechnologies for obtaining convenient-to-use dry bacterial concentrates for direct application and liquid enzymes that do not require additional preparation of the production starter and simplify the cheese production process are also widespread [54], which helps minimize the risk of secondary contamination by foreign microflora and the influence of bacteriophages. In particular, when domestic scientists use a fresh sample of a liquid aqueous preparation extracted from the secretory cells of the calf stomach, the time for milk coagulation and milk clot formation is quite long and is about 2.5 hours (159 min). However, when stored at 4 °C for up to 18 months, the coagulation time decreases to 48 min, apparently due to increased levels of chymosin and other extractive enzymes. In the production of Carpathian cheese and budz, it is recommended to use such an amount of a highly specific preparation that ensures the onset of milk coagulation at 33–35 °C after 20–5 min, which is similar to the action of the natural coagulation enzyme chymosin, but without the cleavage of αS1- and β-casein substrates [55,56].

Rennet soft cheeses are valuable protein products with varying fat content and taste, which, depending on the coagulation process, starter cultures, enzymes, and production technology, differ from cheeses made exclusively by fermentation with starter cultures, but do not differ from hard cheeses made with various types of enzymes. The cheesemaking enzyme Rennet/Rennin is most often a natural preparation of the hydrolase enzyme (animal rennet, rennet, gastric enzyme) obtained from the stomachs (rennet) of dairy calves or lambs, consists of two hydrolase coagulant components: calf chymosin (hydrolyzes casein protein, destroying casein micelles, and coagulates, connecting casein proteins and the calcium-phosphate complex of milk) and beef pepsin (A and B, the main digestive enzyme, breaks down proteins into peptides and amino acids), and their ratio varies depending on the age of the animals. Rennet enzyme contains mainly

chymosin (80% to 95%) and pepsin (20%), both of which enhance coagulation.

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Rennin (a mixture of chymosin and pepsin or pure chymosin) is obtained not only from animal resources but also by microbiological means. Rennet enzyme (rennin) is often confused in everyday life due to the similarity of names with renal enzyme (renin), which is an active (direct, free) hormonal proteolytic enzyme produced by kidney cells and performs a different biological function: regulates blood pressure and water-salt metabolism in the body, but in terms of the chemical structure of the active center it is close to pepsin, is a product of the REN gene, consists of 340 amino acid residues, affects angiotensinogen (product of the AGT gene), participates in the breakdown of proteins, mainly angiotensinogen. The enzyme chymosin (rennet) is a highly specific proteolytic enzyme in gastric juice that breaks down kappa-casein, destroys protein micelles, causes rapid coagulation of milk, forming a dense clot, and provides the texture and taste of cheeses. Pepsin, which is produced by the glands of the gastric mucosa, is activated in an acidic environment (pH = 1.5–2) from its inactive form (pepsinogen) by hydrochloric acid and breaks down proteins into peptides and amino acids. Chymosin (from calf rennet or artificially grown) is best suited for the production of hard and semi-soft cheeses, coagulates milk at pH 3–4 (natural) or pH 4–5 (synthetic) in the presence of calcium ions (calcium chloride to improve the structure of the pasteurized milk clot — 1 g per 10–12 l).

The classic method of obtaining an "Italian" flavor profile (spiciness, creaminess, aroma) is to introduce the natural enzyme calf lipase (2 g per 100 l of milk), obtained from the anterior gastric glands of young calves, which breaks down fats, releasing free fatty acids, and accelerates the ripening of cheeses, which is critically important for hard cheeses (Parmesan, provolone) and many types of cheese. Italian-made "Clerici" lipases do not contain pancreatic or microbial lipases, and the main difference from pancreatic and microbial lipases is that they mainly release long-chain fatty acids, which are responsible for unusual flavors [57].

The current trend in enriching functional products with fatty acids to increase nutritional value is to make the fat content more beneficial (polyunsaturated omega-3, monounsaturated fats) and add new flavors [58], which is achieved by adding flaxseed oil or nut butter, which are also an additional source of vitamins, minerals and antioxidants, but requires control over the formation of a dense clot (calcium-magnesium bridge) and the process of syneresis (whey separation), since too much fat can "envelop" the protein.

Microbial enzymes (vegetarian enzymes) are produced by deep fermentation of plant substrate or fermentation of non-genetically modified fungi *Rhizomucor miehei (Mucor miehei), Cryphonectria (Endothia) parasitica, Rhizomucor miehei,* and lactic acid yeast *Kluveromyces lactis* by several manufacturers. The increase in cheese production worldwide has led to a decrease in the supply of animal rennet, which has increased the demand for new coagulant substitutes, such as proteases of plant origin [59], either under the influence of lactic acid, or microbial starter compositions having a complex complex of enzymes that ensure the cleavage of protein molecules during the transformation of cheese mass components during the ripening process.

Cheesemaking uses animal, microbial, and plant enzymes with an activity index of IMCU — International Milk Coagulation Units, which is given in Table 3.

Analysis of research shows that Ukrainian cheeses need to update their recipes, since their ripening period is only 35–60 days, compared to European cheeses (on average, 223 days) [20, 60–63]. In the production of hard rennet cheeses, the most problematic aspect is the selection of bacterial starter cultures and their quantities (Table 2), with the dominance of recombinant preparations (*CHY-MAX*, etc.), which ensure stable product yield. In

Table 3

Characteristics and producers of some animal, plant, and microbial enzymes in cheesemaking

Enzyme group by origin	Type of active ingredient and biochemical features	Examples of commercial preparations	Manufacturer, country
Animal (natural) — dry, liquid	Rennet (80–95%), pepsin (5–20%). Obtained by maceration of the calf abomasum. Ideal for cheeses with a long ripening period. Liquid — 92/8	Natural Calf Rennet, Natural EXTRA, Berthelot 530	Alce International S.R.L, (MOFIN ALCE Group Italy); Famille Granday (France)
Microbial (coagulants)	**Microbial rennin (proteases).** Produced by the fungus *Rhizomucor miehei.* Temperature-resistant, suitable for fresh and brine cheeses.	Marzyme MT 2200, Valiren, Meito (on bran)	Danisco France SAS (France); Mayasan (Turkey); Meito (Japan)
Recombinant (genetically engineered)	**100% chymosin (FPH/FAH).** Obtained by fermentation of *Aspergillus niger* or *Kluyveromyces lactis*. High purity, no bitterness during maturation.	CHY-MAX (I, II generation), RENMAX 600L, Astro Chymosin Ideal-100% Chymosin	Chr. Hansen (Danmark); Mayasan (Turkey); Calza Clemente (Italy); Ideal still exim srl (Romania)
Combined and special	**Mixtures of chymosin and pepsin (50/50, 80/20).** Stabilized for coagulation strength (800-1000 IMCU/ml). For high-quality soft and semi-hard cheeses	Clerici 50/50; Rosso 80/20 Alce; Reniplus NG 50G; Rennet liquid 92/8 Clerici	Alce International S.R.L.,(Italy); Caglificio Clerici (Italy); Grupo Proquiga (Spain)

Source: author's development based on data from manufacturing companies.

contrast, for authentic brine cheeses (Brynza, Suluguni), the use of microbial proteases (*Meito, Valiren*) remains appropriate due to their cost-effectiveness and rapid coagulation. The formation of organoleptic indicators in rennet cheeses is associated with increased total bacterial starter, increased milk acidity, and reduced cheese grain mixing duration [64].

The increase in cheese production worldwide has led to a decrease in the supply of animal rennet, which has increased the demand for new coagulant substitutes, such as proteases of plant origin or under the influence of lactic acid, or microbial starter compositions, which have a complex complex of enzymes that ensure the cleavage of the protein molecule during the transformation of the components of the cheese mass during the ripening process. The shift from traditional starters has promoted the inoculation of milk with symbiotic starters, followed by coagulation with animal (rennet), plant, or microbial (rennet) enzymes [65].

Optimization, modernization, and innovation in technologies, acceleration of the fermentation, coagulation, and ripening of hard cheeses, and the search for alternative cheeses are modern challenges for cheesemakers. However, new premium products are appearing on the market. The most effective way is to use protective starter cultures and introduce functional components or active additives. Replacing rennet with plant enzymes, as well as the search for natural preservatives, expands the range of vegan bioproducts. In the global market, consumers demand various types of cheeses, particularly those with additives and extracts that affect the characteristics of biotechnological fermentation cultures used to produce a wide range of traditional and functional fermented milk products and bacterial preparations. At the Cheese Art Festival — ProCheese Awards 2025 (Kyiv), in the national competition for the best Ukrainian cheese among more than eight dozen cheeses submitted for evaluation by an international jury, the gold award went to Brunost cheese with roasted walnuts and dried cranberries from the European Cheese Factory (LLC "Shabska Farm", in the Odesa region).

The selection of the optimal enzyme complex (Table 2) and direct-introduction starters (Table 3) is crucial. We believe that for brine-ripened cheeses, the use of thermophilic strains in combination with recombinant chymosin creates an ideal proteolytic base that subsequently allows the integration of additional bioactive components.

Scientists point to the potential to use a wide range of functional, flavor, aromatic, and other additives in the production of soft cheeses, which can contribute to the development of new, healthy, enriched types of cheeses (Table 4).

Table 4

Functional and technological potential of Biopreservative and Phytoadditive in cheese production

Component	Biologically active substances	Function in cheese biotechnology	Impact on safety and quality
Biopreservative	Bacteriocin (natur. Antibiotic)	Inhibition of gram-positive bacteria (*Listeria, Clostridium*)	Prolonging shelf life, preventing "late swelling" (Clean Label)
Phytoadditive (Fenugreek)	Galactomannans, steroidal saponins, flavonoids	Prebiotic support for starter cultures, antioxidant effect	Formation of a nutty flavor, enrichment with iodine, iron, and vitamins
Synergistic effect	A complex of bacteriocins and phytoncides	Creating a "double barrier" (Hurdle technology)	Stability of organoleptic indicators as table salt content decreases (Green Deal)

Source: author's development based on data from manufacturing companies.

Innovative research allows vegetarians to choose cheeses that use a non-animal enzyme, usually labeled on the packaging as "microbial" (rennin) or "non-animal rennet" (plant protease), which replaces the animal enzyme (rennet). Plant proteases have high potential, particularly as milk coagulants for cheese production, and there is technological feasibility in using new types of fermented herbaceous plants with protease enzymes that break down proteins into amino acids and promote their absorption [66]. Scientists have conducted numerous studies on plant enzymes isolated from aqueous plant extracts, characterized by the proteolytic-to-coagulation activity ratio [67]. Studies of plant enzymes isolated from aqueous extracts, in particular enzymes from papaya (*Carica papaya* — papain), pineapple (*Ananas comosus* — bromelain), kiwi (*Hayward* — actinidin), fig (*Ficus carica* — ficin), cardoon (*Cynara cardunculus — cynarin, quercetin, rutin*), to obtain a popular substitute for cheeses such as brynza, and enzymes from other plants characterized by a specific ratio of proteolytic and coagulation activities (insufficiently high or excessively high proteolytic activity for the production of commercial cheeses) [59].

According to the data presented in Table 3, direct-injection starters are optimal for this process; the use of phytoadditives, in particular, plant apple fiber, did not cause significant changes in organoleptic indicators due to their characteristics, contributing to an increase in the yield of the finished product by 3.7 [68].

Cheeses made with plant coagulants usually have lower cheese density but are characterized by higher protein digestibility (up to 90–95% for certain types). However, plant coagulants have certain limitations, mainly related to the texture and sensory quality of the cheeses produced. Plant proteases (papain, bromelain) often act too aggressively, breaking down casein into small peptides, which can give the cheese a bitter taste and produce a weak, loose, and tender cheese that easily breaks when cut [69].

It is also recommended to use various supplements such as elamin (a kelp extract that is 95% digestible by the body), spirulina, pollen, stevioside, crude extract from the leaves of Calotropis gigantea/procera, or other vitamin supplements. In particular, the Singaporean company Sophie's BioNutrients, in collaboration with the American ingredient giant Ingredion Idea Labs, has developed a vegan alternative to dairy-free and lactose-free cheese based on microalgae, creating a plant-based cheese substitute rich in vitamin B12 [70]. Ingredion Idea Labs has global expertise in consumer analytics, applied research, practical knowledge, and technological processes across 30 innovation centers worldwide. Startups Better Dairy, Those Vegan Cowboys, and Standing Ovation are creating cheese without cow's milk through precision fermentation The incorporation of phytonutrients into functional fermented milk beverages has shown positive results in studies of bio-drinks, particularly regarding their nutritional and health benefits [71, 72].

In the research on the development of fresh cheese, crude extracts from calotropis leaves were also used as alternative milk coagulants, namely freeze-dried extracts of *Cynara humilis L.* (CH) and *Onopordum platylepis* Murb. (OP), The mineral and protein content were investigated, and their coagulation and proteolytic activities were compared with *Cynara cardunculus L.* (CC). The effects of extract concentration (5–40 mg extract/ml), temperature (20–85 °C), pH (5–8), and $CaCl_2$ concentration (5–70 mM) on the milk clotting activity (MCA) of CC, CH, and OP extracts were evaluated. MCA values were

significantly higher in CC at the same extract concentration. The extract that showed the most significant increase in coagulation activity with increasing temperature was OP, reaching a maximum at 70 °C. The pH value for maximum milk coagulation was 5.0 for both CC and CH, whereas for OP it was 5.5. $CaCl_2$ increased the coagulation capacity of the extracts, especially for OP and CH. In addition, proteolytic activity (PA) and hydrolysis rate increased with increasing time and enzyme concentration, with CC achieving the highest caseinolytic activity.

Cheeses made with plant protease enzymes from the genus *Cynara* L. have a smooth, creamy texture and a refined taste, which explains why these perennial herbaceous plants have been used since ancient times to produce traditional cheeses. The proteolytic activity of *Cynara enzymes* (cardosines) is more intense and more specific than that of animal rennet. Cheeses made with plant-based proteases from the aster genus *Cynara* L. have a smooth, creamy texture and a refined taste, which explains why these perennial herbaceous plants have been used to produce traditional cheeses since ancient times. The most famous species, such as *Cynara scolymus* L. and *Cynara cardunculus*, are cultivated as valuable food and medicinal plants that contain vitamins (C, K), minerals (magnesium, potassium), and the antioxidant compound cynarin. This method is the basis for the production of many traditional cheeses, especially in Spain (Torta del Casar) and Portugal (Queso de la Serena or Queijo Serra da Estrela), where the use of plant-based rennet is part of the cultural heritage [73].

Liquid rennet, a microbiological enzyme, is also recommended — an enzymatic preparation obtained through controlled fermentation of *Rhizomucor miehei* [74]. Also, alternative cheese enzymes from microbial rennin obtained by microbial fermentation — vegetarian enzyme Browin (*Rhizomucor miehei*) rennin (1–5 g per 100 l of cow, goat, soy milk), with an activity of 2250 IMCU/ml, introduced at a temperature of 70–72 °C (manufacturer Biowin, Poland) [75].

Control of innovative implementations. Phytoenzymes in coagulation require consideration of possible process risks. Despite the advantages of plant-based enzymes (e.g., papain, ficin, bromelain) for expanding the range of vegetarian products, their large-scale industrial implementation poses clear risks to process reproducibility. The main problem is the variable catalytic activity of crude plant extracts, which is strongly influenced by crop seasonality, geography, and extraction methodology. In contrast to standardized animal rennet or microbial chymosin, unstandardized phytoenzymes often exhibit non-specific proteolytic activity. Prolonged or uncontrolled proteolysis destroys the casein matrix, leading to high whey solids losses, reduced cheese yield, and accumulation of hydrophobic bitter peptides during ripening. To ensure batch-to-batch consistency, industrial implementation requires pre-standardized commercial herbal preparations calibrated in International Milk Clotting Units (IMCU), strict real-time monitoring of coagulation temperature (optimized between 32 and 36 °C), and precise pH control to limit excessive residual enzymatic activity after pressing.

Food control, especially for craft semi-hard and fresh soft cheeses, is carried out by quantitative risk assessment. Acid adaptation and survival of *Listeria monocytogenes* in fresh cheese are determined by protective lactic acid bacteria. *Lactobacillus paracasei 4341* is used as an auxiliary culture to enhance the taste of short-ripened cheeses such as Caciotta or in traditional Minas cheeses. One of the Italian cheeses, among the delicacies and unique types of caciotta, has many regional variations from different types of milk: cow, sheep, goat, or even buffalo (Ukrainian caciotta is made from buffalo milk at the TasBio farm in the Chernihiv region). Caciotta with truffle is made from a mixture of cow's and sheep's milk. Keijo Minas is a Brazilian fresh or slightly aged cow's milk cheese, characterized by a soft texture and delicate flavor, rather than a standard hard cheese. It can be young (white) or aged (harder), but it does not belong to the classic hard varieties [76].

Cheesemakers are studying the use of multifunctional strains of lactic acid bacteria in the pilot production of feta cheese, in particular, the effect of probiotic additional cultures on the characteristics of low-fat feta cheese, the effect of intact and immobilized cultures of *Lactobacillus casei ATCC 393* on whey protein as starters for the production of probiotic feta cheese, and the improvement of the quality and safety of Greek functional feta cheese using a strain of *Lactobacillus plantarum* with probiotic potential [77].

To ensure the quality of industrial bioproducts, it is recommended to consider the raw materials, recipe, technological parameters, and sanitary and hygienic conditions of production, as unforeseen factors can pose risks during the development of a safe food product with stable characteristics and

quality features in technological processes. As of 2026, methods for assessing milk coagulation continue to be used in Ukraine, in particular the fermentation test (rennet fermentation test), which is used to control microbiological quality, especially in cheese production. This method allows you to assess the enzymatic activity of microflora and the compliance of milk with coagulation requirements. The test is based on the ability of the microflora in raw milk to coagulate under the action of rennet enzyme and to thermostate at (38–40 °C) for (12–24 h). Assessment by classes: Class I (Best): The cheese is dense, smooth, without gas bubbles, and whey is not released or is released slightly. Such milk is suitable for cheesemaking. Class II (Suitable): The cheese is dense, but may have single gas bubbles. Class III (Unsuitable): The cheese is torn, spongy, has many gas bubbles, or is swollen. Such milk is not used for cheesemaking.

Mechanisms of biochemical transformations in the nutraceutical profile of alternative cheeses. Specific and qualitative characteristics of cheeses are formed under the influence of biochemical processes caused by the microflora of cheese and technological conditions of its production [53]. Bacteriostatic drugs of a wide spectrum of action, which are associated with a violation of the process of protein synthesis in the microbial cell, inhibit the growth and reproduction of bacteria, especially most gram-positive and gram-negative microorganisms, such as *Escherichia coli, Shigella flexneri* spp., *Shigella boydii* spp., and *Shigella sonnei, Antagonistic properties* and antibiotic resistance are studied using biochemical and microbiological methods with the antibiotics chloramphenicol, gentamicin, doxycycline, amoxicillin, kanamycin, streptomycin, penicillin, nystatin, ceftriaxone, and cefotaxime (at concentrations of 10–80 μg). Antibiotics (benzylpenicillin, fumagillin, bacitracin, sarcidin) inhibit the development of a relatively limited number of bacterial species, therefore, the antibiotics tetracyclines (tetracycline, oxytetracycline, metacycline), chloramphenicol (chloramphenicol), carboxypenicillins (carbenicillin, carfecillin, carindacillin, ticarcillin), ureidopenicillins (azlocillin, mezlocillin, piperacillin), cephalosporins, macrolides, and fluoroquinolones inhibit the development of phagocytized microorganisms, and therefore they are used as clinical antibiotics to eliminate infectious diseases.

The technological characteristics of bactericidal sourdough strains enable their use for controlling *Listeria monocytogenes* in cheese. The polymerase chain reaction method is used to determine the subspecies of *L. lactis strains* [78]. It is important to recreate and preserve such a microbiome in cheesemaking when creating innovative sourdoughs that meet the requirements of DSTU 4554:2006 "Fermented milk cheese. Technical conditions", where the microflora requirements are based on lactic acid bacteria that are unique and provide fermentation (usually not less than 1×10^6 CFU/g). Protective starter cultures suppress undesirable microflora in milk during its technological processing by biological means, including *Listeria, Clostridium, Salmonella spp., Pseudomonas*, yeast, and mold fungi. Contaminated food products can be non-infectious or infectious (microbial). Infectious poisonings are caused by pathogens, including those that cause salmonellosis, dysentery, and food poisoning. The most common pathogens of food poisoning are enteropathogenic *Escherichia coli O157:H7*, RNA virus *Norovirus GII* from the *Caliciviridae family, Salmonella* spp., *Yersinia enterocolitica*, intestinal clostridia *Campylobacter* spp., *Campylobacter fetus jejuni, Clostridium perfringens, Bacillus cereus, Staphylococcus aureus, Listeria monocytogenes, Shigella,* etc. *Listeria monocytogenes* was identified as a major hazard, assessed in modeling studies by scientists using available modeling approaches developed for the dynamic nature of the cheese production process, and identified the main microbial target of concern and factors influencing microbial behavior in these products (pH, aw, lactic acid concentration, and temperature were the main factors considered as independent variables in the models). Classical two-stage modeling is the most common approach for developing predictive microbiological models, thereby deepening knowledge of cheese production and storage [79].

Some protective cultures can reduce oxidative processes in milk, namely, prevent early oxidation of fat and thereby prevent bitterness in the finished product, while maintaining total microbial contamination below the limit established by the Codex Alimentarius. The fundamental difference of domestic bacterial starters "Iprovit" (produced by the Department of Biotechnology of the Institute of Food Resources of the National Academy of Sciences of Ukraine) is that from the isolation of new strains of lactic acid microorganisms, bifidobacteria included in their composition (optimal ratio of *Lactobacillus acidophilus, Leuconostoc lactis*, as well as *Bifidobacterium*), selected exclusively from natural sources in Ukraine,

without the use of genetic modification methods, live cultures are highly active, have probiotic properties — normalize digestion, promote the elimination of toxic substances from the body and ensure the naturalness of the final fermented milk product [80]. French bioprotective starter cultures BIOPROX (manufacturer Bioprox Cultures) are widely used for biological protection of cheeses, suppressing pathogenic microflora, mold and yeast without the use of artificial preservatives, developed for biological protection of cheeses, yogurts and sour cream, suppress mold and yeast without affecting acidity — high-quality cultures for cheesemaking (mesophilic, thermophilic, protective), ensuring stable quality, aroma and texture of cheeses. Popular series: main protective culture (*Lactobacillus rhamnosus* and *Lactobacillus plantarum*) and a series of freeze-dried cultures for direct use DI-PROX (series DI-PROX M127 — mesophilic starter for cheeses, consisting of *Lactococcus lactis* subsp. *Lactis, L. lactis* subsp. *cremoris, L. lactis* var. *diacetylactis*., series *DI-PROX M401* — lyophilized mixture of mesophilic heterofermentative cultures for cheeses and fermented milk cheese (cheese), some of which have medium proteolytic potential and protective properties for fresh and soft cheeses [81]. As a protective starter, the direct-application preparation RSF–742 (Chr. Hansen, Denmark) is used, which contains the following lactic acid bacterial strains: *Lactococcus lactis* subsp. *cremoris, Lactococcus lactis* subsp. *Lactis, Streptococcus thermophilus, Lactobacillus helveticus*. To ensure long-term storage of the produced cheese, it is recommended to add the protective culture Fresh Q (Chr. Hansen, Denmark), which includes *Lactobacillus rhamnosus*, directly to the milk together with the main starter at a temperature of 32–40 °C to protect against harmful yeast and mold microflora in the production of fermented milk cheese (cottage cheese), as well as yogurt, sour cream, kefir and fermented baked milk, extending the period of freshness and contributing to the formation of a more pronounced creamy taste in the studied samples [82].

Innovative biotechnological developments in cheese production are discussed in articles on the development and application of protective probiotic bacterial cultures containing high concentrations of viable cells (10^{10}–10^{11} CFU/g) as next-generation preparations to improve the technological properties of food products [83].

In addition to the use of protective cultures, maintaining the desired level of food safety and production is achieved through effective antimicrobial mixtures, particularly nisin. However, studies show that combining nisin with other antimicrobials in milk and cheese effectively increases shelf life, thereby reducing the risk of undesirable microbial growth. Scientists warn about microorganisms, mainly gram-positive bacteria, which pose a threat to food safety, namely: *L. monocytogenes, Listeria innocua, Clostridium botulinum, Streptococcus thermophiles, Staphylococcus aureus* and *S. bovis,* which can adapt to the preservative nisin, which may lead to a decrease in its effectiveness, especially when using low concentrations that do not kill bacteria, but only inhibit their growth, but can acquire resistance to nisin. The following pathogenic microorganisms acquire signs of resistance by species: *L. monocytogenes* (develops resistance through changes in the lipid composition of the membrane and the expression of cold shock proteins — Csps); *Clostridium botulinum* (spores are more resistant than vegetative cells; gradual exposure to nisin forms resistant strains); *Staphylococcus aureus* (acquires resistance through mutations in the NsaRS system, which leads to constitutive activation of the VraDE transporter) [84, 85].

Hurdle Technology Effect. To deepen the study of the influence of biopreservatives in cheesemaking, we investigated patterns of change in the physicochemical, microbiological, and organoleptic parameters of fermented milk cheese, as a function of raw milk quality and the concentration of the natural preservative nisin, across different stages of the technological cycle. Also, we developed the biotechnology of fermented milk cheese with an extended shelf life, based on the use of a biopreservative and a consortium of lactic acid bacteria [86].

In research and production technologies, preservatives, particularly natural nisin, are added to raw materials or finished products to inhibit the growth of microflora and prevent biochemical processes involving microorganisms. Scientists have established that nisin is widely used as a safe biopreservative, the effectiveness of which, of course, is affected by the fat content and acidity of the medium, being especially active in sour cheese. Depending on the type of cheese, nisin is added in different concentrations within 0.005–0.01% and the sequence of technological processes, for

example, for hard cheeses — 0.1 g per 20 l of pasteurized milk before fermentation, or nisin is added to finished cheeses such as Ricotta — 20–100 mg/kg or to processed cheese — 0.1–0.6 g per 1 kg of finished product to extend the shelf life [87].

The addition of nisin to cheese is not just for its preservative properties. However, as a component that reduces the heat load on the raw material and lowers the salt content (NaCl) in the brine, thereby making the cheese safer, i.e., the use of barrier technology methods guarantees the elimination or control of pathogens in food. Bioregulators, saponins, and flavonoids of fenugreek apparently have a probiotic effect on the antioxidant status of cheese, thereby creating a nutraceutical profile for such cheeses.

For the development of biotechnologically-based brine cheeses with phytonutrients (fenugreek), mesothermophilic mixtures were chosen (Table 3) because they provide an optimal balance between rapid lactic acid accumulation and the development of an aromatic profile that synergizes with fenugreek essential oils. The use of nisin and fenugreek in the cheese formulation emphasizes the barrier effect, extending shelf life and providing safe protection against contamination (Hurdle Technology) in the K-Health model for improved health. In the context of combating food fraud and microbial infections, the use of natural bacteriocins such as nisin is a strategic tool for ensuring biosecurity without synthetic preservatives (Table 5).

Quantitative Efficacy of the 'Double Barrier' System. The synergetic mechanism of the proposed 'Double Barrier' system relies on distinct yet complementary pathways of nisin and Trigonella foenum-graecum (fenugreek) extracts. Peer-reviewed quantitative data indicate that commercial nisin exhibits a Minimum Inhibitory Concentration (MIC) against key Gram-positive contaminants, such as Listeria monocytogenes and Staphylococcus aureus, in the range of 100–300 IU/g, achieving a 2.5–4.0 log reduction in bacterial counts during the first 14 days of ripening. Conversely, fenugreek extracts, rich in steroidal saponins (e.g., diosgenin) and flavonoids, primarily target Gram-negative strains (e.g., Escherichia coli, Pseudomonas spp.) and molds, with MIC values ranging from 0.5% to 1.5% (w/v). The synergy manifests as sub-inhibitory concentrations of fenugreek saponins alter lipid bilayer permeability in bacterial cell membranes. This structural disruption lowers the threshold for nisin-induced pore formation, reducing the required effective dose of both agents by 20–30% and broadening the spectrum of antimicrobial protection without altering the native lactic acid bacteria (LAB) starter dynamics.

Technological integration. However, the main protection against harmful microbial contamination is compliance with the regulated purity and sterility of production and use of high-quality starter cultures, in particular, starter components, lactic acid bacteria *Lactococcus lactis*, *Lactobacillus*, which have received the generally recognized status of GRAS (safe), which create an acidic environment, inhibiting the growth of pathogenic microflora, producing lactic acid, hydrogen peroxide and bacteriocins during fermentation. Pasteurization and hygienic storage conditions for cheeses are very important, even though cheeses are considered safe products; they can be affected by saprophytes that do not cause infectious diseases but are pests that violate technological parameters [88 The Kharkiv company "AVS. Climat" provides services on the Ukrainian market for the production, maintenance, and sale of refrigeration equipment, particularly for cheese storage. Important conditions for storing cheeses are high humidity (80–90%) and temperature, 2–8 °C.In particular, young cheese is well stored at a temperature of 5–7 °C (up to 10 days), soft cheese at 2–5 °C and humidity of 85–95% (up to 5 days), and aged sliced cheeses can be stored at 7–15 °C for up to a month. Hard varieties require less humidity than soft ones, are stored at 13–16 °C with humidity of 80% or above, and on shelves at room temperature, with mesophilic bacteria (Gouda) up to 20 °C and thermophilic bacteria (Maasdam) up to 18 °C. In general, cheeses feel good at 5–15 °°C, with a relative humidity of at least 80% and moderate air circulation. Fatty cheeses ripen under relatively low temperatures (12–15 °C) and a relative humidity of 90–95%. The shelf life of brine cheeses at 2–5 °C is up to 6 months. (which are ripened and stored in 16–20% salt brine after molding), which requires additional research.

Optimization of the technological process of soft cheese production with phytoadditives, to obtain a synergistic effect of the effective concentration of the initial lactic acid starter (MCS) and the optimized dose of coagulating enzymes on the process of cheese structure formation in combination with the calculated safe bactericidal concentrations of phytoadditives, will ensure a stable bioprocess of fermentation with the production of cheeses of a nutraceutical profile. Based on the analysis

Table 5

Technological separation of cheese fermentation components

Component	Role in biotechnology	Examples
Phyto-enzymes	Catalysis: replacing animal rennet with plant proteases for protein coagulation	Artichoke extracts, papain or cardoon-based developments
Phyto-additives (*Trigonella foenum-graecum*)	Modification: changing the nutrient profile, organoleptics, and prebiotic support	Fenugreek, flaxseed, herbal extracts
Bio-preservatives (Nisin)	Protection: inhibiting unwanted microflora without chemical additives	Nisin, natamycin, protective cultures

Source: author's development.

(Tables 2 and 3), the need to create combined systems was determined, taking into account the influence of the phytoadditive on the kinetics of acid formation, the cheese's microstructure, and the processes of ripening in brine.

When modeling the general principle biotechnological scheme of the process (Fig. 2) with parameter regimes for the corresponding stages of production of a cheese bioproduct with phytoadditives such as classic fermented milk cheese or brynza, based on the specified technological parameters, a conceptual biotechnological scheme of the sequence of introduction of the biopreservative and food energy should be developed. Optimization of technological parameters (fermentation temperature, holding time, and dosage of the phytoadditive-biopreservative) will enable the production of a product with increased biological value and improved functional properties (fenugreek provides an antioxidant barrier and a nutraceutical effect, and nisin provides microbiological safety without chemical load).

The developed biotechnological scheme of the target bioproduct includes the main biotechnological stages of the technological process — PreF (PT, HT); FP; PostF, DS [86] — growing biomass of seed material of the inoculation complex of symbiotic starter of the appropriate composition, fermentation, fermentation of the milk medium and coagulation of the curd mass to curd grains, as well as auxiliary stages — preparation of milk (nutrient medium), preparation of seed material and packaging and storage of the target product and additional waste disposal operations.

Standards. Codex Standard 243-2003 (Standard for Fermented Milk), FAO/WHO, applies to fermented milk, including heat-treated (Heat Treated Fermented Milk), as well as to composite dairy products based on them; Codex Alimentarius (2017). General Standard for Food Additives (GSFA). FAO/WHO.Joint Standards Program. Codex Alimentarius (2022). General Standard for Cheese (CXS 283-1978). FAO/WHO is an international benchmark that many countries use to base their legislation and to adhere to ISO 9001, ISO 22000, and HACCP standards. Since January 1, 2026, updated rules for sampling and laboratory testing have been applied in Ukraine. In addition to the fermentation test, control for antibiotic residues, somatic cells, and general bacterial contamination is mandatory in accordance with the requirements of the Order of the Ministry of Agrarian Policy of Ukraine dated 25.11.2024 No. 4150. In Ukraine, there are a significant number of enterprises (large national dairy corporations and medium-sized regional enterprises) specializing in the

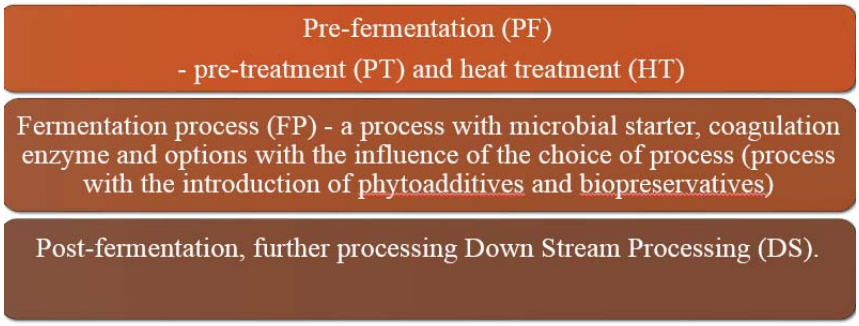


Fig. 2. **The main stages of the principal biotechnological flowchart of the fermentation production process (PreF, PT, HT, FP, PostF, DS)**

Source: author's development based on a classical biotechnological scheme.

production of high-quality cheese products, which play an important role in shaping the assortment and supplying the domestic market with high-quality cheeses.

Marketing and consumer advocacy against imports. Analyzing the cheese market and perceptions of competition in the import market, given that imports from Poland (43.8%) and Germany (15.9%) dominate the domestic market, Ukrainian producers clearly need to adopt targeted differentiation strategies. Consumer sentiment analysis indicates a growing preference for health-oriented products without additives (the Clean Label and K-Health concepts). The use of fenugreek, which has a unique marketing advantage (its natural organoleptic profile and characteristic nutty flavor in imported European premium cheeses such as Alpine or Gouda, with additives), and the use of nisin instead of synthetic preservatives help protect cheese during storage. By promoting the dual-benefit narrative of these bioadditives (a familiar, popular premium taste combined with natural biological protection) for domestic brands, they can justify a competitive price in the mid- to premium price segments. This strategy allows local functional cheeses to directly compete with premium EU imports on supermarket shelves, appealing to both taste preferences and health awareness under the "K-Health" model.

Conclusions

Justification of market trends and modernization. Analysis of global forecasts for the development of the dairy industry indicates stable expansion of the cheese market until 2033, with a pronounced dominance of the Specialty Cheese and functional products segments. This aligns with our conclusions regarding the potential of Ukrainian brine cheeses, which, to enter international markets, require biotechnological modernization to intensify and optimize ripening periods without compromising basic organoleptic and physicochemical quality indicators.

Optimization of the enzymatic-microbial complex. The selection of the optimal enzymatic complex and direct-introduction starter cultures (DVS — Direct Vat Set) is a decisive factor in integrating the fermentation bioprocess into cheesemaking. It is justified to use thermophilic strains in combination with recombinant chymosin for brine cheeses, as this combination creates an ideal proteolytic basis that facilitates the integration of additional bioactive components.

Experimental validation of the "Double Barrier" concept. Based on experimental studies, the high efficiency of applying barrier technology (Hurdle Technology) principles in cheesemaking has been demonstrated. A promising direction that follows from this analysis is the combination of biopreservation (nisin) and phytocorrection (fenugreek) within the framework of the "Double Barrier" concept. Although these technologies are often considered separately, particularly in our previous experimental studies, their synergistic combination in the "K-Health" model addresses microbiological safety concerns without synthetic additives. This approach fully complies with the principles of "Clean Label" and "Green Deal" in the modern food bioindustry..

Prospects for industrial implementation and biosafety. The proposed comprehensive model of technological process modernization (including the conceptual scheme PreF — FP — PostF — DS) opens new opportunities to scale up the production of competitive functional cheeses. The implementation of this model at domestic enterprises ensures strict compliance with the current requirements of Ukrainian legislation regarding the control of raw material safety (in particular, residues of inhibitory substances, somatic cells, and SBO in accordance with the Order of the Ministry of Agrarian Policy No. 4150 of November 25, 2024), guaranteeing stable reproducibility of the bioprocess in real production conditions. The proposed comprehensive model for modernizing the technological process opens new opportunities for creating competitive functional cheeses. Further development in this direction will allow adaptation of theoretical developments to the conditions of real production at Ukrainian enterprises.

Author contributions

O. Sh. — conceptualization, study design, data collection, drafting the manuscript, and original draft preparation. critical revision, manuscript editing, translation editing, and language polishing. and final approval of the manuscript. Authors have read and agreed to the published version of the manuscript; Z. H. — literature review; O. V. — experimental studies; T. L. — results discution.

Funding

This research received no external funding.

Conflict of interest

The authors declare no conflict of interest.

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РОЗВИТОК ТА ОПТИМІЗАЦІЯ БІОТЕХНОЛОГІЇ СИРІВ З ФІТОДОБАВКАМИ ТА БІОКОНСЕРВАНТАМИ

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Подано систематичний аналіз стратегій розвитку світового та вітчизняного ринку сирів, зосереджуючись на впровадженні біотехнологічних інновацій. Обґрунтовано доцільність використання при оптимальному співвідношені молочно кислих заквасок та сичужного ферменту або фітоферментів і фітодобавок чи біоконсервантів для розробки ферментованих та розсільних сирів у рамках моделі «K-Health», з акцентом на індивідуалізованому харчуванні шляхом функціональної ферментації у контексті гармонізації вітчизняних технологій з міжнародними стандартами безпеки (ISO 22000:2018, *Codex Alimentarius*).

Мета. Оцінити вітчизняний ринок сирів та дослідити вплив біотехнологічних параметрів (склад закваски, температура ферментації та методи коагуляції) на структурно-механічні властивості, мікробну стабільність та профілі безпеки сирів, дозрілих у розсолі (таких як бринза), та ферментованих сирів, а також з фітодобавками та біоконсервантами відповідно до стандартів біобезпеки для гармонізації технологічних циклів виробництва сирів.

Матеріали й методи. Проведено методологічний аналіз наукової літератури та нормативно-правових баз з *PubMed, Scopus, Web of Science* та *Google Scholar*, зосереджуючись на інтеграції стартових заквасок, захисних культур. фітоферментів та біоконсервантів у харчову біоіндустрію виробництва сирів.

Результати. Продемонстровано динамічний характер біотехнологічних впроваджень та ефективність альтернативних компонентів, включаючи фітоферменти, у сироваріння Запропоновано концепцію «Подвійного бар'єру», що базується на синергетичному поєднанні біоконсерванту (нізину) та пребіотичної фітодобавки (пажитника), що забезпечує мікробіологічну чистоту білкової матриці, підвищує антиоксидантну стабільність та зміцнює антимікробний бар'єр. доповнюючи унікальну модель оздоровлення «K-Health». Зокрема, для сирів, дозрілих у розсолі, попереднє додавання фітоекстракту в поєднанні з тривалим дозріванням оптимізує розподіл смаку та стабільність матриці. На основі аналізу було визначено необхідність створення комбінованих систем.

Висновки. Інтеграція мікробних та рослинних агентів в біотехнологію ферментованих сирів у рамках концепції «Подвійний бар'єр» створює наукову основу для функціонального сироваріння. дозволяє мінімізувати ризики мікробної контамінації на етапах дозрівання та зберігання, забезпечуючи відповідність вимогам глобальних стандартів безпеки ISO 22000:2018 та *Codex Alimentarius* без використання синтетичних добавок, узгоджуючи сучасні харчові біотехнології з принципами «Чистої етикетки» та «Зеленої угоди».

Ключові слова: харчова біоіндустрія, кисломолочні та тверді сири, розсольний сир, функціональний продукт, молочнокислі бактерії, ферментативна коагуляція, фітоензими, фітодобавки, нізин, біобезпека.

Received 2020/07/22
Revised 2026/08/20
Accepted 2026/10/31