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New technological paradigm of the Russian dairy industry: formation principles under globalisation

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Abstract: The present research employed a convergent approach and cognitive methodology to define the upgrade options in the sphere of domestic dairy industry according to the principles of the 5th technological paradigm. The principles include biological nanomembrane cluster technologies with a complete production cycle. The paper offers a forecast for the 6th technological paradigm, which presupposes picotechnology for the production of milk derivatives, such as lactose hydrolysates, lactulose, microparticulate proteins, peptides, and amino acid pool. The principle makes it possible to return secondary dairy raw materials into the technological cycle. These significant resources include low-fat milk, buttermilk, and especially whey, which can be used to produce functional foods for various population groups, as well as new generation forage resources. From the point of view of logistics, the modern dairy industry should employ a digital and robot-aided non-waste production scheme. Thus, all dairy raw materials should be considered as natural clusters according to the nature-formed biotechnological system (BTS). These clusters are lipids (fats), nitrogen-containing substances (proteins), carbohydrates (lactose), minerals (salt), biologically active substances, and water. As an idealised model of agricultural raw material, milk is extremely complex. Its chemical composition includes more than 2000 constituents and 100000 molecular structures. In addition, dairy architectonics is also extremely complex: milk is suspension, emulsion, and solution, concurrently. Finally, milk possesses unusual physicochemical, osmophoric, structural-mechanical, bio-thermodynamic, and other characteristics. We conducted a long-term systematic analysis and developed a scheme that can help the domestic diary industry to adapt safely to the new technological paradigm. The scheme takes into account various factors, such as limited traditional dairy resources, Russia's accession to the WTO, and the globalisation of the world dairy market. Our research team belongs to the leading federal scientific school 'Living Systems' (No.7510.2010.4) developed by the North Caucasus Federal University (Russia).

Keywords: Milk, whey, nanotechnology, bioproducts, modernization, clusters

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INTRODUCTION

The current food industry as a whole, and dairy industry in particular, fits in the 5th technological paradigm, which is based on biotechnology with relics of the 4th (electricity) and the 3d (mechanics) technological paradigms [1]. The 6th technological paradigm will supposedly originate from the current 5th paradigm in 2025 [1–5]. The possible start date corresponds with Decree No. 350 issued by the President of the Russian Federation on July 21, 2016. The Decree is entitled 'On the Administration of State Science and Technology Policy for the Development of Agriculture'. It defines 2025 as the year by which raw milk production will have increased by 40%. The provisions were further specified in the Presidential Decree 'On the national goals and strategic objectives of the development of the Russian Federation for the period up to 2024' (May 7, 2018). According to Paragraph 7, almost all sectors of Russian economy are to transform to the principles of the best available technologies (BAT) by 2024.

Dairy production is an essential component of the food industry of the historically established agro-industrial sector, i.e. the milk production – dairy products – sales chain. For the new technological paradigm to take power in the current Russian dairy industry, it needs an upgrade [6, 7]. The prospective upgrade is directly related to ensuring food security and independence of the country and its regions [8].

STUDY OBJECTS AND METHODS

The research featured the paradigm of dairy raw materials, which was tested in the dairy industry on the

Table 1 Content of the main constituents in dairy raw materials, g/100 g

Constituents	Whole milk	Skimmed milk	Buttermilk	Milk whey
Milk fat	3.7	0.05	0.5	0.2
Proteins	3.3	3.3	3.3	0.9
Lactose	4.8	4.8	4.7	4.8
Mineral salts	0.7	0.7	0.7	0.6
Solids	12.5	8.8	9.1	6.5

level of Technological Platform formation. The system analysis involved the convergence methodology with elements of the cognitive approach as developed by the Russian Academy of Sciences [4].

Table 1 shows a comparative analysis of raw milk composition, cream excluded, which resulted from mechanical and biotechnological processing.

Skimmed, or rather low-fat, milk and buttermilk are protein-carbohydrate raw materials and have 50% of solids. Whey is a carbohydrate raw material with 70% of solids. Proteins, lipids (milk fat), and carbohydrates (lactose) are the main and most valuable constituents of the secondary dairy raw materials. In addition to the main constituents, skimmed milk, buttermilk, and whey also contain mineral salts, non-protein nitrogenous compounds, vitamins, enzymes, hormones, immune bodies, organic acids, etc. It means that almost all components of milk solids can be utilised, even biologically synthesized water with its memory and fullerenes-kenotrons.

Table 2 provides data on the degree of transition of dairy constituents into dairy protein-carbohydrate raw materials, or secondary dairy raw materials, as defined by the Technological Regulations.

Skimmed milk and buttermilk contain almost the entire protein, carbohydrate, and mineral complex of milk and up to 15% of milk fat. Whey contains carbohydrate complex, proteins, and mineral salts. These data should be taken into account during identification, examination, and industrial processing of secondary dairy raw materials.

Table 2 Degree of transition of the main dairy constituents into the secondary dairy raw materials

Milk constituents (100%)	Degree of transition, %		
	Skimmed milk	Buttermilk	Milk whey
Milk fat	1.4	14.0	5.5
Total protein, including	99.6	99.4	24.3
Casein	99.5	99.5	22.5
Whey proteins	99.8	99.6	95.0
Lactose	99.5	99.4	96.0
Mineral salts	99.8	99.6	98.0
Solids	70.4	72.8	52.0

Table 3 Dispersed composition of dairy clusters

Milk constituents	Size of the molecule or particle, nm	Volume of the molecule or particle, %
Water	0.1–0.2	90.10
Fat	200–10000	4.20
Casein	40–300	2.30
α-Lactoglobulin	5–20	0.30
B-Lactoglobulin	25–50	0.08
Milk sugar (lactose)	1.0–1.5	3.02
Mineral salts	0.1–1.0	0.10
BAS	0.1–100.0	0.01

Table 3 shows the sizes of the structures of the main constituents of dairy raw material.

Dairy raw materials contain all types of structural systems: ions, molecules, colloids, suspensions, and emulsions.

In the Russian Federation, the annual processing volume of dairy raw materials is 30–33 million tons. It means that secondary raw materials are estimated as 20 million tons, which is a huge reserve and available resources for the industrial upgrade. This especially concerns new-generation functional products branded by Prof. Petrovsky as 'minimum of calories – maximum of biological value' [9].

A long-term systematic analysis allowed the team of the North Caucasus Federal University (federal scientific school 'Living Systems' No.7510.2010.4) to offer a scheme that can help the domestic diary industry to adapt safely to the new technological paradigm. The scheme takes into account various factors, such as limited traditional dairy resources (< 50%), Russia's accession to the WTO, and the globalisation of the world dairy market. The generalised scheme has nine fundamental principles, or blocks, and was published in [10]. The principles cover the whole range of dairy production from dairy raw materials to the problems of the international dairy industry, including the organisation of alternative off-season productions. This paper introduces the concept of the second principle, which involves the scaling of innovative, sustainable biological nanomembrane 'high-tech' technologies for industrial processing of dairy raw materials with the complete production cycle [11, 12].

RESULTS AND DISCUSSION

Logistically, dairy industry should implement a zero-waste production scheme that observes the following principle: waste milk is nothing but unused reserves [13]. It was 30–50 years ago that the so-called recycling plants appeared in the global dairy industry. They played a positive economic and social role: they brought in profit, gave workers two days-off, and protected the environment. For example, all large cheese-making factories are to have skimmed milk and whey drying stations. According to the new approach to this problem, dairy constituents are to be obtained from the original milk. Raw materials of plant and animal origin are to be combined to produce such functional products (bioproducts) as pro-, pre-, and synbiotics. In addition, a significant amount of secondary dairy raw materials (milk protein-carbohydrate raw materials) enters the so-called technological cycle. As a result, the industry loses a great deal of skimmed milk, low-fat milk, buttermilk, and especially milk whey, which is responsible for half of the solids of the original raw material, while polluting water sources [14].

To update the dairy industry by implementing modern innovations, the dairy technology platform has to be revised with subsequent access to the new technological paradigm [1, 15, 16]. In the nearest future, the industry will have to comprehend and implement the large-scale high-tech options. According to Metz [11, 17, 18], the 5th technological paradigm will include food nanotechnology [19] with biomembrane and baromembrane processes aimed at the clusters of dairy constituents with the use of information and communication technologies. The European Economic Community set up the first European Institute for Food Industry (EU-IFP) (http://www.hightecheurope.com). It has three branches: Biotechnology (BIOTECH), Nanotechnology (NANOTECH), and Information and Communication Technology (ICTECH) [20].

On the industrial level, the innovative priorities of technological upgrade have the following principles.

Epistemologically, all dairy raw materials – whole and skimmed (low-fat) milk, cream, buttermilk, and whey – are constantly renewable resources. Therefore, the food obtained from them can be viewed upon as objects of rapidly developing nanotechnology. Hence, their constituents at the molecular level should be considered as naturally synthesized clusters of simple (molecules, atoms) or complex (micelles, aggregates, particles) compounds [20]. The cluster structure of the main components of dairy raw materials creates prerequisites for directional and controlled modelling, i.e. bio-technology in the 5th technological paradigm and picotechnology in the 6th.

Similarly, from the point of view of the nature-formed biotechnological system, all components of dairy raw materials can be considered as natural clusters – lipids (fat), nitrogen (proteins), carbohydrates (lactose), minerals (salt), biologically active substances, and water. As an idealised model of agricultural raw material, milk is extremely complex. Its chemical composition includes more than 2000 constituents and 100000 molecular structures. In addition, dairy architectonics is also extremely complex: it includes suspension, emulsion, and solution. Finally, milk possesses unusual physicochemical, osmophoric, structural-mechanical, bio-thermodynamic, and other characteristics.

Milk as a biotechnological system provides new-born mammals with nutrients and can serve as a basis for next-generation high-grade foods. According to its physical and chemical properties, its active acidity and osmotic pressure are close to the nutriciology of mammals. Thus, it can be of practical importance that proteins, milk sugar, and mineral salts increase the density of dairy raw materials, while milk fat reduces it.

As a biotechnological system, dairy raw materials illustrate the opinion voiced by the great Russian physiologist and Nobel Prize winner Pavlov: ‘milk is an amazing food prepared by nature itself.’ Structurally, this is a heterogeneous system in the form of a solution intended for direct (oral) use. It has a sufficiently high content of solids, particles (milk fat in the form of suspension or emulsion), colloids (proteins and mineral compounds), and a molecular solution (lactose, mineral salts, and BAS). Milks obtained from sheep, goats, mares, camels, and buffalos differ from cow’s milk as a complex biotechnological system. This should be considered in industrial processing. The same applies to their secondary dairy raw materials, e.g. skimmed milk, buttermilk, and whey [23].

In 2007, we introduced the concept, or doctrine, of nano-, bio-, membrane, and biomembrane technologies to implement this principle. The concept was published in food industry journals and tested at food industry seminars and international summits in 2008, 2009, 2011, 2015, and 2016. Apparently, it can serve as an alternative basis for the industry upgrade [24].

The fundamental paradigm of nano-food technology in the dairy business can be confirmed by the processes of synthesis of lactose derivatives [25, 26]. For instance, the biological nanotechnology of lactose hydrolysis produces two monoses from lactose disaccharide (1 nm), i.e. glucose and galactose with a size of 0.5 nm. This solves the problem of milk intolerance. The Stavropolsky Dairy Plant (Stavropol, Russia) used this unique procedure to obtain marketable low-lactose milk under the Healthy City programme. The globally famous synthesis of lactulose at the proton level, which is pure nanotechnology, is the pride of the industry and has proved to be extremely profitable [27]. Lactulose is known to be the best prebiotic, a bifidobacteria promoter, and an ideal natural laxative. A research in its production and implementation was awarded the Prize of the Russian Federation Government on Science and Technology in 2002.

The last decade has seen a fundamentally new direction of dairy nanotechnology: whey proteins are microparticulated into nanotubes that imitate the flavour of milk fat [28]. The industry has already mastered the logistics for the formation of microgranules (nanotubes) of whey proteins from the so-called ‘albumin milk’. Such products are well known abroad under the Simplesse brand [23]. This innovation has also been implemented in Russia [12, 29].

Biotechnology of dairy products is historically associated with pure cultures of microorganisms in the form of starter cultures and enzymatic catalysis that are used to obtain such fermented milk products as sour cream, cheese, cottage cheese, and dairy beverages.

High-biotech solutions have a long history in the domestic industry. Sour cream is known as traditional 'Russian cream'; sour clotted milk is a Russian biocenosis; kefir is traditionally favoured by the centenarians from the Caucasus; yogurts, or 'dairy ferments' were introduced by the famous Russian Nobel Prize winner Mechnikov as part of lactotherapy, etc. Such elements of superbiotechnologies as enzymatic catalysis and microbial synthesis have long been part of centuries-old cheese-making procedures. Unique biotechnologies of dairy industry are as sophisticated as the finest surgical operations and require the same disinfection measures. Some of them can be adapted to obtain starter cultures in controlled fermentation procedures for silage making, sauerkraut production, meat industry, as well as in medicine and veterinary. According to Luff, the 'life code' that nature and bionanotechnology give to industrially processed whey provides people with immune protection against many diseases, including various flu strain [23, 30]. As for milk lactose, Canadian veterinarian De Lookk called it the 'saviour of mankind' because it can prevent and treat salmonellosis [31].

One of the most promising biotech solutions in the dairy industry is the production of derivatives of the nitrogen-containing milk complex, namely casein and whey proteins. It deserves special consideration. It involves two separation methods: hydrolysis and proteolysis. Casein hydrolysis is well-studied and globally implemented, e.g. in pharmacy. Its biotechnology is based on the proteolysis of caseins in cheese, which determines the type and quality of products. The hydrolysis of whey proteins is of particular importance in the biomedical aspect since it is used in infant formulae, as well as in dietary and therapeutic nutrition.

The amino acid composition of whey proteins is believed to be closest to human muscle tissue [32]. They exceed all other animal and vegetable proteins according to the content of essential amino acids and branched-chain amino acids (BCAA), e.g. valine, leucine, and isoleucine. According to the FAO/WHO, the biological value of albumin and globulin, which are the main whey proteins, exceeds the ideal 100 cu ascribed to eggs. It amounts to 104 cu, which is twice as high as the biological value of wheat. This corresponds with the traditional Russian proverb that bread and milk are the best food. The digestibility of whey proteins is 98%, which is extremely high. Table 4 illustrates the data on the content of some essential amino acids according to the scale used by the FAO/WHO and their presence in whey proteins.

Table 4 Content of essential amino acids

Amino acids	Content, g/100 g of protein	
	FAO/WHO scale	Whey proteins
Isoleucine	4. 0	6.2
Leucine	7.0	12.3
Lysine	5.5	9.1
Methionine + Cystine	3.5	5.7
Phenylalanine + Tyrosine	6.0	8.2
Threonine	4.0	5.2
Tryptophan	1.0	2.2
Valine	5.0	8.7

Numerous peptides and amino acids are extremely important for human health, especially those natural polypeptide chains that can be found in dairy raw materials. They can also be obtained artificially from casein fractions and polypeptide chains of whey proteins. For instance, exomorphins are natural painkillers. They regulate the general endocrine profile of mammals and produce a soothing effect on cubs. As for β-casomorphins, they are excellent immunomodulators. 'Dairy peptides' increase the phagocytic activity of certain gastrointestinal bacteria, thus ensuring resistance to infectious diseases. For example, the Institute of Biophysics (Siberian Branch of the Russian Academy of Sciences) has synthesized lactoptin, an analogue of breast milk low molecular weight peptide. It possesses antitumor and antimetastatic properties and is absolutely safe [33]. Angiogenin (Milkang) is beneficial for blood vessels and heals wounds and burns [34]. Unfortunately, the issue remains largely understudied.

The process is extremely complex, and its results can be implemented in various ways. One can mention the studies of phenylketonuria performed at the Kemerovo Institute of Technology (University) [35]. The proprietary technology of obtaining biologically active peptides from milk proteins has been implemented on an industrial scale in England. The Molvest company (Voronezh, Russia) has started to produce dairy products with reduced antigenicity using the controlled hydrolysis of β-globulin into peptides. The technology was developed by the combined efforts of A. Bach Research Institute, the Russian Academy of Sciences, the Interindustry Scientific Center of the Siberian Research Institute of Mining Geomechanics and Surveying and the Voronezh State University of Engineering Technologies [36].

Baromembrane technology makes it possible to separate high molecular weight polydisperse liquid systems, as shown in Fig. 1. It has been adapted to dairy raw materials, especially ultrafiltration and electrodialysis [37, 38].

Figure 2 shows installations that use baromembrane methods of molecular sieve separation of whey.

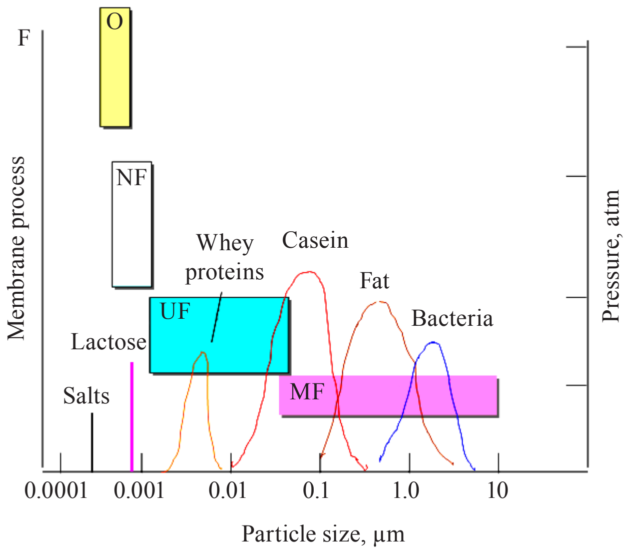


Figure 1 Diagrams of baromembrane separation of constituents of dairy raw materials: RO – reverse osmosis, NF – nanofiltration, UF – ultrafiltration, MF – microfiltration

The illustrations demonstrate the achievements and prospective scaling of the industry. As for electroflotation, sorption, desorption, and ion exchange, they are still under research and are undergoing experimental testing.

Electrodialysis desalting of whey produces up to 100000 tons annually and increases by 30% each year. Such a large-scale production has made it possible to reduce the export of solids, which were purchased from as far away as Argentina. Now it is a full sub-industry of dairy production. To demonstrate the process, Figure 3 shows the scheme of electrodialysis and devices of domestic production.

Biomembrane technology. There has been a series of long-term case studies performed by Prof. Molochnikov's team. The studies were conducted by the joint efforts of the Institute of Organoelement Compounds (Moscow) and a number of medical institutions, such as the Institute of Aviation and Space Medicine (Moscow), Ministry of Defence, Institute of Nutrition (USSR Academy of Medical Sciences), All-Union Scientific Cancer Centre (Moscow). The researches have made it possible to review and fundamentally change the approaches to raw milk processing and the composition and quality of dairy products [39–42].

The studies employed the biomembrane technology: an aqueous solution of a polysaccharide, e.g. pectin, is introduced into milk raw materials, i.e. natural or condensed skimmed milk, reconstituted milk powder, or buttermilk. Milk casein is thermodynamically incompatible with polysaccharide. As a result, casein-

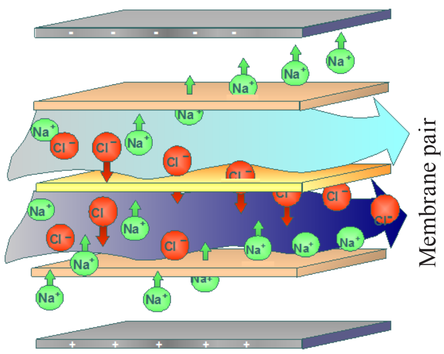
Microfiltration

Ultrafiltration

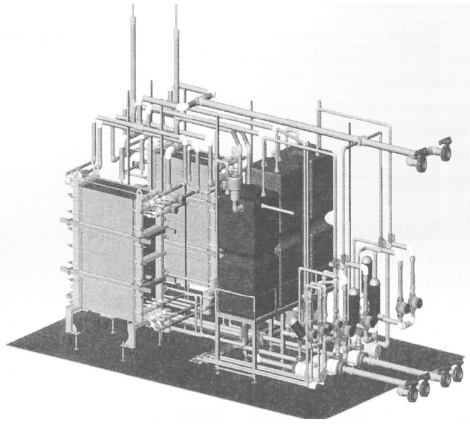
Nanofiltration

Reverse osmosis

Figure 2 Baromembrane installations for molecular sieve filtration of whey



(a)



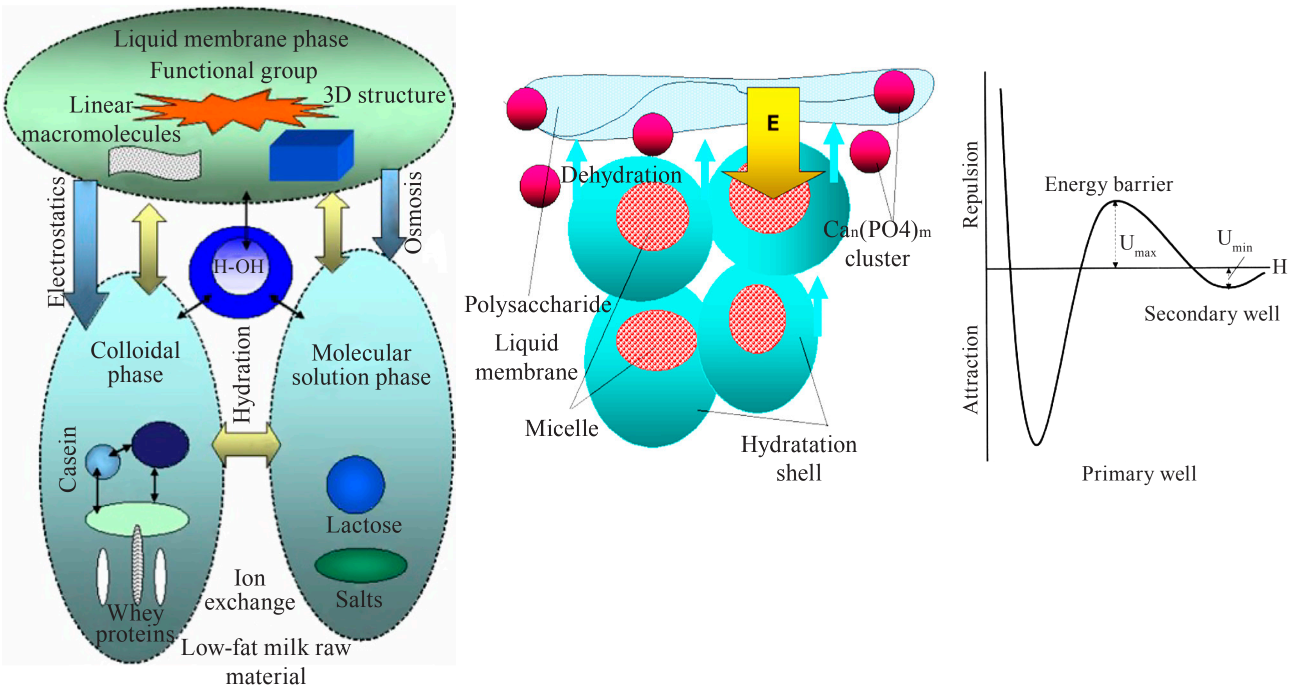
(b)

Figure 3 Schematic diagram of whey demineralisation (a) and a module of Istok electrodialysis installation (b)

containing dairy raw materials spontaneously split into two liquid fractions – natural casein concentrate (NCC) and a whey-polysaccharide fraction (WPF). After that, the two liquid raw materials are separated by gravity or centrifuged. They are easily combined with the remaining dairy raw materials. The initial raw materials can be processed, and no by-products are formed, which corresponds with the principles of zero-waste technology with a closed zero-discharge production.

Figure 4 illustrates a hypothetical simulation model of the interaction between the liquid membrane (a polysaccharide solution, e.g. pectin) and the main milk constituents. The system's stability is modelled according to the DLVO theory (Derjaguin + Landau + Verwey + Overbeek) [43].

In general, basic researches in academic institutions and programme-targeted studies conducted by industry research institutes on the issue of biomembrane technology with the Bio-Ton dairy product line give every reason to revise the existing principles of production in the dairy industry. This can serve as a basis for the 6th technological paradigm in accordance with the principles of the system approach [44]. The 6th technological paradigm presupposes sono- and



(a) (b) (c)

Figure 4 Hypothetical model of the interaction between the liquid membrane and the milk constituents (a); formation of associates of the first level casein micelles (b)$ and the interaction energy curve according to the DLVO theory (c) picotechnologies with a full automation under aseptic conditions, i.e. unmanned technologies.

The abovementioned data make it possible to imagine the complexity of the problems and their solutions based on modern genomics, proteomics (peptidomics), lipidomics, and genetic engineering. Their practical implementation in the form of nano-, bio-, membrane, and biomembrane technologies can shape a fundamentally new dairy science – LactoOmics [7, 45–48]. The issue has to be considered separately on the principles of cognitive approach and convergence methodology within the framework of the new technological paradigm [49].

The concept was adapted for milk whey, which was named 'universal agricultural raw material' by Prof. Lipatov [50]. The research team was represented by members of the Scientific and Educational Centre 'Membrane BioTechnologies' and the engineering BioCentre of the North Caucasus Federal University, which belong to the scientific school No.7510.2010.4. The proposed concept of bionomembrane technologies fully complies with the principles of the 5th technological paradigm with its high-tech (1985–2025) and creates real prerequisites for the 6th technological paradigm (2025–2080). The latter will employ picotechnology and elements of artificial intelligence (neural networks) to produce food and fodders of the new generation. The concept is outlined in a manual for the new generation of industry professionals [51].

CONCLUSION

On the eve of the 6th technological paradigm and the BAT principles, the dairy industry as we know it has to be upgraded [52, 53]. The upgrade will require tremendous efforts. The principles of LactoOmics listed in [55] have to be implemented in practice [54]. Only the fundamental principles of food technology will make it possible to avoid the tragedies of such manufactured famines as Holodomor [56–60]. Now that Russia has joined the WTO, the globalisation of the world dairy market requires an adequate response.

CONFLICT OF INTEREST

The authors declare that the authenticity of the issue makes any conflict of interests impossible. The research results were only published in the Bulletin of the Russian Academy of Sciences, which was mentioned in the text.

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