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Emerging Trends in Food and Dairy Technology for Sustainable Nutrition and Public Health

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Abstract

Food systems are essential for nutrition, health, and well-being. Yet, despite such vast numbers of hungry people (more than 840 million) and the reports that about 1.9 billion adults are overweight (or obese), the double-burden continues. Inappropriate food intake during early life and unhealthy diet-caused non-communicable diseases harm children's growth and development. The problems are aggravated further by the global climatic changes and rising consumer concerns over food safety. In this regard, dairy science has become a vital subject area for fostering food security, safety and sustainability around the world. By 2050, the world's population is expected to reach between 10 and 11 billion. Thus, today's food supply chain is facing grave and urgent issues, including climate change, population growth, food safety issues, new contaminants and environmental consequences. A fundamental transformation towards sustainable food systems must take place that promotes public health, food security and environmental sustainability. The food industry must stand for a sustainable system of food distribution that reduces GHG emissions and saves natural resources. The dairy sector is perishable in nature, which is a very important food security component. It plays a very critical role in improving nutrition, health and overall well-being of poor and rich populations alike. In developing countries, milk has become an important nutrient for young children and a source of income for mothers. On the other hand, the dairy products continue to be widely eaten in developed countries and are an important source of protein and other nutrients. (2022 - Hassoun et al.).

Keywords: *Dairy, nutrition, food safety, health, technology, sustainability, education, digitalisation.*

1. Introduction

In 2050, the world population is projected to be 9.5 to 10 billion. The rising population and urbanisation will lead to increased demand for food, which will help producers to increase food diversity, quality and supply security while also achieving sustainability goals (Hassoun et al., 2023). The World Health Organisation (WHO) estimates that 31 million people die from diseases caused by the choice and consumption of food each year. Food safety is very important, and continuous R&D is the need of the hour for ensuring the safety of dairy products. In the dairy business, waste generation is roughly 30% of the total milk processed, signifying poor process optimisation. High-value by-products like whey and lactose have limited markets and have yet to be fully valorised.

2. Innovations in Dairy Processing and Product Development

Due to increased health issues related to nutrition and sedentary lifestyle patterns, the importance of nutrition in the prevention of Non-communicable diseases (NCD) has gained global prominence. After COVID-19 and public health lessons, we are moving towards the next big issue in the world: food sustainability. As much as 33% of all food produced is wasted, triggering experts to call for urgent increases in food production by 2050. The nutritional market is likely to undergo significant changes in response to digitalisation and the younger generations becoming more health-conscious. Quality nutrition is not affordable and accessible in low- and middle-income countries (LMICs). The ever-expanding portfolio of dairy products offers opportunities to address chronic non-communicable diseases (NCDs) via various dairy foods and beverages, refocus attention on the affordability of food, examine opportunities of plant-dairy hybrids, and combat these global threats.

2.1. Novel Cultures and Fermentation Technologies

Recent innovations in fermentation and dairy technologies and products are largely driven by new consumer expectations and other socio-economic, environmental and health considerations. The rise in population and global urbanization, as well as the consolidation of the industry, has increased the requirement for easily available, tasty, and flavourful food and beverage products (Capozzi et al., 2020) The use of innovative techniques in these industrial processes will improve food safety and

will help to offer more safe and nutritious dairy (Tsafrakidou et al., 2020). The increasing popularity of artisanal and fermented food products is creating a demand for new dairy ingredient sources, as well as for cultures that expand the range of flavours and textures available.

Due to these factors, there is worldwide interest in product development and fermentation. Fermentation not only generates flavouring and structural agents but also improves safety by generating antimicrobial agents. Eating fermented foods may help reduce the risk of developing some chronic diseases, making products made by fermentation

especially important for preventive health. The introduction of products fermented without dairy and alternative proteins has extended the range of ingredients. Processing and analytical technologies are improved for safety, quality and nutritional assurance.

2.2. Membrane Filtration and Valorisation of Dairy By-Products

The whey, permeate, and cheese whey by-products are generated during dairy processing. They hold valorisation potential as they have lactose, proteins, bioactive peptides, lipids, vitamins, minerals and other valuable components. The streams often have nil market value and are discarded or underused.

Membrane filtration is capable of concentrating and/or purifying protein fractions for subsequent further processing or inclusion in fortified products. The resulting retentate and permeate are carbohydrate-rich and can be used as ingredients in other matrices (Kumar et al., 2013). Membrane filtration is a well-established process in the dairy sector. It enhances the recovery of proteins and other components, optimises the quality of different products, creates new products and achieves better economic gain from milk, all while ensuring safety and nutritional value.

2.3. Alternative Dairy Proteins and Plant-Dairy Hybrids

The rising health and sustainability concerns about dairy consumption are the driving force behind alternative dairy proteins and dairy-plant hybrids. People have health, environment, animal welfare and personal choice issues with dairy products. More and more consumers are looking to eliminate dairy or turn to alternative proteins due to health concerns like lactose intolerance and milk allergy, while others are undergoing dietary change for sustainability or ethical reasons (Hu et al., 2022). Researchers are becoming increasingly interested in alternative dairy proteins such as those derived from plants and

plant–dairy hybrids that combine dairy and plant proteins.

The incorporation of both plant and animal proteins ensures that plant–dairy hybrid products are a good introductory option for interested consumers. These items can enable people to manage their lactose intolerance along with important nutrients, with a high-protein option, too. The deliberate empirical studies are to solve commonly mentioned issues in their field regarding the palatability and functionality, which include taste, stability, sedimentation, mouthfeel and viscosity, foaming, emulsification and heat stability.

3. Food Safety, Quality, and Nutrition Assurance

Food safety, traceability, and hygiene assessments influence consumer confidence and provide a competitive advantage in a fast-evolving market driven by health awareness and risk perception. Major threats to food safety include biological, chemical, and physical hazards, with biological threats and subsequent loss of shelf life considered the most dangerous (Batt & Noonan, 2009). Pathogenic bacteria are a primary concern in all stages of the dairy supply chain (Zhao & Huang, 2011). Increasingly complex multi-hurdle processing for dairy shelf life and safety control has created the need for rapid process monitoring, pathogen detection, and screening for chemical contaminants.

Nutritional profiling, bioavailability assessment and fortification tools help to provide timely guidance in product development so that dairy products are tailored to meet the needs of diverse target populations. The lack of dietary protein and calcium affects large shares of the populations of many countries with high dairy consumption. There is a continued interest in allergen management, especially in relation to dairy and plant-based alternatives. Screening methods for 14 allergens at industry speed make marketed alternative dairy products label-ready. Food transparency and authenticity are always in the spotlight. As demand increases for clear labelling of dairy foods and ingredients, so too does the expansion of targeted technologies for effective dairy-species identification, origin tracing, and component integrity verification.

3.1. Rapid Methods for Pathogen Detection and Hygiene Monitoring

Microorganisms like bacteria and fungi find an ideal substrate in various dairy products. Dairy processing plants may allow foodborne pathogens and spoilage microorganisms to enter through raw milk, surfaces, equipment, air, and personnel. It is a challenge to maintain

food safety and quality during storage, transport and distribution. Risk-based approaches can facilitate intervention strategies and control measures more efficiently. Supply-chain partners can use rapid testing to validate compliance to ensure safety, quality and shelf life. Traditional methods of plating can take days and are not suitable for rapid testing. No rapid tests are available for many relevant pathogens or contaminants. The lack of guidelines or norms for rapid methods inhibits their further development and implementation (O'Grady et al., 2020). More and more quick methods involve modern technologies like biosensors, microfluidics, on-chip, and nanotechnologies (Vidic et al., 2019). APAC, North America, and Western Europe lead the research landscape.

3.2. Nutritional Profiling, Bioavailability, and Fortification

The nutritional value, bioavailability, and fortifying foods are becoming of growing interest to food processors (Fardet et al., 2019) as the health impact of food consumption becomes widely known. A food matrix can have a significant impact on health effects through modulating the release and absorption of nutrients. As a result, when we take complex edibles, the bioavailability and release kinetics of nutrients are more relevant compared to food supplements. It is therefore recommended to take a holistic approach to maintaining the food structure of the raw material. Dietary fibres have different health benefits based on their characteristics. It is worth noticing that the investigation of structure–function relationships has continued to reveal significant microstructural changes occurring during digestion, such as the increased bioaccessibility of vitamin D3 from fortified cheeses due to an increase in the protein-to-fat ratio and of interfacial surface area of fat globules (Nuria Castaneda Lazo, 2016). There are other factors which influence the availability of nutrients, which bad the prediction of nutrient bioavailability universally. These include the physicochemical properties of foods, the kinetics of digestion, and individual differences. Strategies of fortification, such as adding more calcium to beverages, target improved nutrient intake as well as their release and absorption.

3.3. Allergen Management and Consumer Transparency

Undeclared allergens in foods and ingredients intended for young children still pose a problem in the EU. These possible contaminants arise from processes involving raw materials or products that cannot be fully eliminated during industrial production. Labelled allergenic ingredients that cross-react to

the actual included ingredients can also be a source of undeclared allergens and therefore, should be subjected to the same obligations as the allergen itself. Although manufacturers deploy various allergen management practices to control cross-contact and allergen risk, their practice efficiency varies, as illustrated by the large number of notifications regarding undeclared allergens still received. For instance, the estimated cost of allergen management in the food industry before the implementation of Regulation No.1169/2011 was about €20,000 per annum per company in a sector worth nearly €36 billion (Martínez-Pineda & Yagüe-Ruiz, 2022).

Considerable, formalised actions taken by companies intending to mitigate the risk of undeclared allergens are not sufficiently recorded or shared, despite an upward trend in the overall number of notifications since the Regulation has been enforced, and the established threshold still does not show signs of formal adoption among the Member States involved. The food industry nonetheless responds to only 1 % of the notifications received at the EU level concerning allergens, which highlights the disparity between the relative importance of these products in a menu intended for young children from other adult-targeted products. Moreover, all food products aimed either directly or indirectly at this population group are usually manufactured with ingredients or raw materials that themselves fulfil the obligations set by the Regulation in the respective Member State, in addition to demanding obligations to manage allergens.

4. Sustainability Through Resource-Efficient Practices

Globally, energy and water account for the highest shares of dairy processing inputs. Using renewable energy instead of fossil fuels can concurrently be an efficient alternative to the depleting natural resources (Knorr et al., 2020). Energy-efficient methods or processes also contribute to economic development. The estimated national average for energy-use efficiency decreases, and energy-transforming efficiency rises are 2 % and increase by 0.76 % annually in dairy production. It is very crucial to pay attention to energy changes within the processing procedure.

Water is necessarily desired during milk processing. The dairy processing industry is humongous with water and energy consumption. Modern media are available to save fresh water accordingly. The efficiency of energy conservation in the utilisation of biomass, landfill, and waste disposal must be taken seriously into consideration. Treatment and usage of acid whey will support a sustainable

processing system. Whey has a high amount of organic alcohol and protein. The formation of vegetable and dairy strategies for detection is lacking.

4.1. Energy- and Water-Efficient Dairy Processing

Energy-efficient processes that minimise or prevent the use of heat, such as high-pressure technologies, microwave treatments, and thermosonde industrial systems, can cut costs and environmental impacts. They can also reduce energy use at the distribution and storage stages (Picart-Palmade et al., 2019). Non-thermal treatments may also extend shelf life and improve food safety. Quite apart from energy savings, some new approaches in on-farm bioprocessing and food transformation are being proposed to increase efficiency still further (Hassoun et al., 2023).

The global food system faces serious sustainability issues: weak energy efficiency; excessive water consumption; high greenhouse gas emissions; limited resource valorisation; and significant food waste. These weaknesses tend to be symptomatic of specific sectors, including food processing, which alone accounts for about 25% of worldwide water consumption and contributes substantially to water pollution, organic waste generation, and the carbon footprint of the agriculture sector. Processing and distribution operations generate 15–20% of the total greenhouse gases emitted by a typical food-processing industry.

4.2. Waste Minimisation, Valorisation, and Circular Economy

The characteristics of food and dairy waste affect downstream processing options and added-value opportunities. A mixture of dairy wastewaters and/or solid streams such as whey permeate, skim, separated cream, etc., can be pre-screened to identify the most suitable processing options. By-product streams from different dairy processes could have complementary compositions, and mixtures can also be beneficial (Roy et al., 2023). The aim is to minimise the amount of wastewater and utilise it as a source of raw materials and nutrients to produce new or reprocessed value-added products. By applying membrane technology combined with the well-established recovery of protein, fats, pigments, and added-value compounds from the process configuration, it is possible to valorise separated waste streams and generate a circular economy of pH, conductivity, colour, and organic fraction around dairy processing (de la Caba et al., 2018).

4.3. Life Cycle Assessment and Sustainable Diet Alignment

To make progress towards the United Nations Sustainable Development Goals

(SDGs), policy strategies must be adopted that target food consumption patterns and align them with climate objectives. Synergies exist between healthy diets free from ultra-processed food and the provision of both human and planetary health benefits (Jolliet, 2022). Consumption of dairy-based beverages assists in meeting healthy and environmentally-conscious dietary guidelines. With respect to the carbon footprint marker, milk has been shown to deliver a favourable impact compared to soya; furthermore, the degree of processing is crucial, with natural yoghourt offering less environmental damage than those that are flavoured (A. Mcauliffe et al., 2018). Further progress and tools are, however, still needed to take into account multi-functionality associated with many food options (L Unger et al., 2024).

5. Digitalisation and Data-Driven Nutrition

The dairy industry is being rejuvenated by digital technology and data, which can manage, monitor, and shape the production process. The adoption of new-age technologies like Artificial Intelligence, Internet of Things, Big Data, Robotics, 3D Printing, and Blockchain is gradually transforming the way farming is done to the way food is consumed. Through these innovations, resources are optimally utilised, product quality improves, and new dairy products are created to fight against climate change and food security. The digitalisation will continue to revolutionise the production of milk, cheese and other dairy products for sustainable food at the factory level (Hassoun et al., 2023).

The digital sector is likewise witnessing an accelerated growth in the establishment of novel agri-food products and methods, notably plant-based alternatives, as a response to environmental, health, ethical, and geopolitical pressures on food systems. The challenge of rapidly and accurately designing and constructing such solutions, however, has intensified. Digital technologies such as big data analytics and artificial intelligence play an increasingly important role in monitoring, consuming, designing, and proposing to consumers food and non-food alternatives, enabling the design of new safe consumable products. These technologies further allow the evaluation of products' environmental footprints, enhancing design decision processes.

5.1. Smart Packaging, Traceability, and Blockchain in Dairy Supply Chains

Ensuring the quality and sustainability of dairy products is an enormous challenge in the complex dairy supply chain. Digitalisation processes are being implemented to collect and disseminate a

wide range of data from the farm to the fork. The incorporation of AR technology facilitates smart packaging that connects with consumers' gadgets, enabling them to access details about the product's origin and traceability (Hassoun et al., 2023). According to Guruswamy et al. (2022), ink-based QR codes readable by smartphones would enable provenance tracing entities and safety compliance verification. Data on ingredients obtained from diverse food processes and their bioavailability are integrated into cloud-based mobile apps to enhance nutrification valuation. Blockchain technology is being used to verify your product's traceability and safety compliance at every level of the supply chain. These data-sharing systems are confidence-building to consumers, foster nutrition transparency, and make dairy products more attractive and competitive.

5.2. Predictive Analytics for Demand, Quality, and Safety

Shoppers are more conscious about the safety and quality of the food that they can buy from a food retailer, restaurant, or other retail venue. Though food quality and safety monitoring during production is essential, recalls of food items occur frequently (Ding et al., 2023). However, many food manufacturers do not sufficiently do this. The usefulness of predictive analytics is huge in managing food supply chains, as it provides forecasts of demand and prices at multiple levels. Forecasting food quality change and monitoring production environments similarly. Keeping a close eye on the quality of products either while they are being made or while they are waiting in storage, as well as chemical sensing of environmental factors such as temperature, pressure and moisture, is already commonplace. More advanced spectroscopic sensor. Predictive analytics helps improve food safety and traceability as well. By looking at past information like data, we can assess risks associated with manufacturing processes and environmental conditions, and even predict a hazard or drop in quality.

5.3. Consumer-Centric Nutrition Guidance and Personalisation

Nutrition research has shifted recently from determining estimates of average requirements to incorporating the regular daily intake variability of individuals. According to V. Matusheski et al. (2021), these developments will help in understanding the biological mechanisms behind variation through the inclusion of genetics and other factors. More personalised food choices and nutrition advice can result from the knowledge learned through nutrigenomics and metabolomics, which offer tremendous potential for improving health and well-being (Menta et al., 2022).

These developments can help lactose intolerants, who may tailor their diets for improved nutrition for calcium intake and metabolism.

Dairy research is currently undergoing digital transformation, with data-based models being developed to predict quality parameters, shelf-life, and safety and to model dairy production and processing (submission 1). Deep-learning algorithms hold the promise of recognising undesired changes in dairy products over time, enabling timely interventions (submission 2). Combining predictive analytical models with information about each individual's metabolome could enhance understanding of nutritional responses to specific foods (submission 3).

6. Public Health Implications

Due to new technologies, food and dairy processing increasingly aims at public health objectives aligned with the UN Sustainable Development Goals (SDGs). Priorities vary from food safety and waste reduction to safe, affordable nutrition and nutritional access by vulnerable populations (Hassoun et al., 2023). Dairy-based nutrition helps in the development of your brain and growth during the first 1000 days. An estimated 118 million children under five years of age worldwide are wasted and/or overweight, and 5.7 million meet the criterion for stunted status. Almost 75 food and nutrition crises in 45 countries threaten food availability, access and utilisation (J. Groot & E. van't Hooft, 2016). Moreover, the combination of different staples and dairy-based diets promotes nutrient security across the life cycle.

Whole milk that has had its milk fat removed to a percentage less than 0.5 has been linked to a lower risk of being overweight in youth, lower factors of metabolic abnormalities in adults and lower risk of diabetes in low-income populations. Plant-source diets have similar effects to animal-source ultra-processed diets. There are many misconceptions about dairy, and educating consumers would, ultimately, help them make informed health choices. The use of risk assessment tools and market-oriented metrics to promote scientifically accurate messages can further enhance dairy's contribution to healthy public nutrition.

6.1. Dairy-Based Nutrition in Early Life and Vulnerable Populations

All over the world, early life and vulnerable populations don't have access to appropriate foods for their growth and development. Vitamins, minerals, and protein of high quality. Dairy foods are nutrient-rich foods, and their consumption is important for them. It is

in addition to the multiple staple food sources in these groups' diets. In numerous countries, including many in Africa, milk is consumed in large quantities, and sour milk products are well integrated into the food culture. According to the research of Haile and Headey (2023), milk consumption is growing, which is consistent with the food safety preference of these groups, as they generally boil milk. Access to milk and dairy products can help in combating deficiencies of various nutrients in early life and in vulnerable groups.

6.2. Impacts on Non-communicable Diseases and Metabolic Health

Nutrition is a key factor to public health policy, with food habits and associated nutritional intakes implicated as major drivers of the incidence of diet-related non-communicable diseases such as obesity, type 2 diabetes and cardiovascular disease (G. Forouhi, 2015). According to D. Poppitt (2020), dairy foods are among the most common and widely eaten foods around the world. Dairy foods help fill nutrient gaps such as energy, protein, calcium, iodine and vitamins A and D. Moreover, dairy foods are among the key sources of calcium, potassium, magnesium, vitamins A and D, riboflavin and protein in our daily diets. Dairy products ferment all over the world. Many countries are touting the benefits of fermented dairy products in their dietary guidelines. Research findings support messages and information that are credible and evidence-based to develop public health guidelines aiming at population groups vulnerable to diet-induced NCDs, including vulnerable groups, at the life stages when health and nutrition habits are formed. Raising awareness of new dairy ingredients, together with creative solutions, will strengthen alignment between the dairy industry and the public health agenda and ensure continuity between and beyond pandemic periods.

6.3. Policy, Regulation, and Public Health Communication

Sustainable nutrition and public health cannot be effectively addressed without sound policies and regulations. Given the extensive, biased, and conflicting information available on nutrition, health, and food—including dairy products—proactive and transparent communication is crucial to identify safe options and to foster individuals' ability to make better-informed choices that align with longer-term diets and lifestyles.

The Canadian government will expand the healthy food asset guide program all over the country. This program helps low-income Canadians, especially Canadians living in food deserts, identify healthy food choices by providing easy

access to resources such as community centres and not-for-profit organisations. The safe food checklists focus on cooling, washing, allergies and cross-contamination. Moreover, studies looked into the impact of obligatory food-labelling programs and specific targeted grants for low-literacy contexts (MacRae et al., 2012).

We need to promote an integrated and multifaceted approach. It is necessary that all sectors, like government, private and civil work collaboratively for dairy and further food and nutrition choices. For producers and suppliers to be able to maintain advice continuity, to be empowered and "skill transferred" and to strengthen validation and resource access, additional technological support is critical.

7. Education, Collaboration, and Ethical Considerations

Human endeavours increasingly depend on scientific and technical developments. Science education embodies principles of inquiry, leading to ever-advanced knowledge and understanding. At the institutional level, education represents a priority. Indeed, educational synergy with the food sector and engagement with society at large underpin many projects. Transformation of food systems constitutes a recognisable need, supporting consideration of ethical frameworks and alignment with society's evolving expectations. On the research side, questions have emerged regarding how transformed food systems can still address essential human needs sustainably (S. Saguy et al., 2024).

Education and training help individuals to realise their dreams and contribute to countries' education targets, and build equitable food systems. With unprecedented changes on a global scale, there is increasing demand for training in food systems, especially interdisciplinary training that highlights the importance of Food Science and Technology (FST). This demand deserves investigation of training needs throughout the food supply chain from raw agricultural commodities to food processing and preservation, sensory enhancement, safety, manufacturing technologies, food delivery, nutrition, and health (Laur et al., 2020).

7.1. Multidisciplinary Training and Workforce Development

In order to deliver nutritious dairy products sustainably, the sector needs to build a diverse and trained workforce that ensures the availability of safe, nutritionally balanced, resource-efficient and ethically produced food. Young people's food and health interests must be reflected in training systems. Many countries invest significant amounts of

money in training systems in the food sector, but these systems might not be generating the competencies required because graduates do not find the food sector attractive (Rovai et al. 2016). The dairy industry needs training that will ensure high-quality, safe and well-packaged dairy products are available on the market; specialists who can assess how products can contribute to healthy diets; methods to optimise the use of resources and reduce waste; modelling tools for the investigation of product, process and system innovations; and the assessment of societal impacts of developments and innovations (Delisle et al., 2017).

7.2. Intellectual Property, Access, and Equity

Innovations are changing the food and nutrition security and state of healthy diets in the world. This must be seen in the positive light of the opportunity it creates to make real changes. Innovations in processing, monitoring safety, assuring nutrition and extending communication at the consumer end will ensure produced food is consumed. Opportunities that reduce unequal access to healthy foods and contribute to the fight against climate change are also emerging. As a result of the divergence between production and dietary goals often being amplified through the processing and consumption of food, expanding innovations towards broader food opportunities can assist in achieving the Sustainable Development Goals (Bonadio, 2016).

Many people think of intellectual property as a way to safeguard investments in research and innovation and to recoup money. As such, it may also prevent access to technologies and products needed for strengthening food systems and enhancing public health and nutrition equity (Williams Zwagerman, 2017). Widespread application could be achieved of dairy technologies, process monitoring and delivery systems can help tackle noncommunicable diseases (NCDs) and support early-life nutrition. Designing intellectual property management can compel a balance of incentives for developing and rewarding with appropriate access to required solutions.

7.3. Responsible Innovation and Food System Transformation

Transformations in food systems aimed at advancing human health, animal health and planetary health must obey new standards of responsibility. A careful consideration of unacceptable research practices, biases and societal inequalities can promote socially acceptable and equitable routes of innovation (Ferraboschi et al., 2022). The dairy sector goes digital to tackle the everlasting issues of the sector. Technologies must

reconcile the responsible handling of nutrition quality and safety, production efficiency and environmental impact according to policy(Hassoun et al., 2023).

8. Conclusion

Different food systems, including dairy, are facing simultaneous challenges because of resource constraints, climate change and public health. Through the promotion of healthy diets with scientific evidence, dairy can remain a relevant, nutrient-dense food with a lower carbon footprint that can help reduce the incidence of non-communicable diseases (Hassoun et al, 2023).

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