A cross-continental animal science perspective on milk fat research: what has happened and where are we heading?

Article

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Summary

Milk is a fundamental food matrix that is widely consumed. Milk fat is important for producing dairy products such as butter, cream, cheese, and whole milk powder. Aside from flavour, it has been linked to human health and its chemistry can be modulated by various means towards more healthy fatty acid profile. Industry and stakeholders have different interests in milk fat, based on specific policies which reflect the type of research and funding initiatives currently performed in different countries. This position paper summarizes the current state-of-the-art with regards to milk fat research, industry, and stakeholder initiatives, and then highlights new developments based on information gathered from North America (United States and Mexico), Europe (United Kingdom, Spain, Italy, and Finland), Africa (Egypt), Asia (China and Bangladesh), and Oceania (New Zealand). South America is an important contributor to the dairy industry but will not be considered and thus this paper must be considered cross-continental rather than global. This manuscript intends to show a wide 'picture' of milk fat from different angles in different parts of the globe.

Keywords: Bovine, consumer perception, dairy science, milk fat, conjugated linoleic acid, industry.

Introduction

Milk and dairy products are a nutritionally important food matrix that is widely consumed in many countries. Milk fat serves as a crucial component to produce standard commodities such as butter, cream, cheese, and whole milk powder (Mohan et al., 2021). Besides its contribution to flavour, fat also plays a role in the technological properties and visual attributes of milk and is associated with the desirable consumer attributes of cream (McCarthy et al., 2017).

From an animal research perspective, some milestones in milk fat research need to be noted. Modifying dietary lipids in ruminant diets has emerged as the most practical, fast, and effective means to change milk fatty acid (FA) profile which started with the aim of increasing milk fat percent by feeding oilseeds to cattle (Wood, 1874). Investigations into effects of dietary fats on dairy cattle were initiated at Cornell University from 1929 until 1943, yielding valuable insights into the role of fats in dairy cow rations (Palmquist and Jenkins, 2017). Subsequently, Reiser (1951) first described the rumen biohydrogenation process, explaining how dietary polyunsaturated fatty acids (PUFA) are transformed into various end-products and by-products, including saturated fatty acids (SFA) and trans fatty acids (TFA) (Bionaz et al., 2020). Notably, the accidental discovery of conjugated linoleic acid (CLA) in 1978 by Michael W. Pariza at the University of Wisconsin while studying mutagens in grilled beef (Pariza et al., 1979) marked a significant turning point in this field and led to extensive research on CLA, particularly rumenic acid (*cis*-9, *trans*-11 CLA), which is almost exclusively found in ruminant derived products, and in some experimental models it has demonstrated to have anti-cancer (i.e., Ko et al., 2020) and anti-inflammatory (i.e., Zheng et al., 2020) properties (Bionaz et al., 2020).

The varying interests of industry and stakeholders in milk fat are mirrored in the policies and research initiatives undertaken in different countries. Therefore, this position paper assimilates knowledge from six regions: North America (United States and Mexico), Europe (United Kingdom, Spain, Italy, and Finland), Africa (Egypt), Asia (China and Bangladesh), and Oceania (New Zealand). This manuscript discusses milk fat research and how it plays a critical role in shaping the future of dairy food technology. The following sections delve into intercontinental research endeavours in the field of milk fat emanating from our research network, fostering a richer understanding of the intricate relationships between milk fat, policy, and research (Figure 1).

This manuscript is a cross-continental narrative research as it involves collaborations between researchers or institutions located in different continents. The manuscript accounts for diverse perspectives where there is access to varied data of global impact but has challenges, such as language barriers, differences in research practices and regulations, and varying cultural norms. Therefore, the variety of discussed information will not be the same for each of the countries. This research reflection does not include South America, and this will warrant further attention as it has made great contributions to the global dairy industry.

All coauthors from this research reflection have worked with milk fat at some point in their careers, and we think the topic has lost attention at least from some parts of the world.

Milk Consumption and milk fat from a consumer perspective

North America

In the US, per capita consumption of fluid milk shows a long-running downward trend (declining by around one half between 1970 and 2019, attributable to shifts in dietary patterns; USDA, 2023). Whilst the introduction of plant-based drinks has contributed to this trend, they are not the primary driver, which is probably related to consumer perception. Also, over the past two decades, US dairy has shifted to decrease in milk fat content and an increase in low-fat cheese production. In 2000, the average milk fat content was 2.01%, decreasing to 1.83% in 2012. However, a subsequent renewed interest of consumers in milk fat led industry to reach an average milk fat content of 2.10% in 2019 (USDA, 2023). The overall consumption of all types of cheese experienced an upsurge with a swifter growth for low-fat types. The current production of American-type cheeses (Cheddar, Colby, Monterey, and Jack) is 44% higher than 2000 levels (USDA, 2023). Nowadays, consumers are becoming much more nutrition-conscious in their beverage choices, so the competition from non-milk beverages increases and a segment of consumers look for milk-based products that are low fat and have high protein and calcium contents and reduced calorie content (Barbano, 2017). However, drinking milk is generally recommended over non-dairy beverages due to positive health effects. For example, a recent meta-analysis suggested that dairy product consumption may have inverse associations with type 2 diabetes risk, mainly due to the anti-diabetogenic effects of dairy fat (Parodi, 2016). The current "Dietary Guidelines for Americans, 2020-2025" recommend daily consuming 2-3 cup-equivalents of dairy products, but it is estimated that only about 10% of the US population meets this guideline.

Mexico has followed a similar trend as the US, with consumption of dairy products and fluid milk decreasing in the past years, and non-dairy products taking important market positions as consumers are more aware of their alleged benefits. In addition, Mexican consumers desire one-stop shopping, driving the growth of hypermarkets and supermarkets. However, inflation in the overall market and lower purchasing power are creating high sensitivity to prices and causing consumers to cut back and seek promotional deals. Opportunities in the region will be at both ends of the spectrum, from premium dairy items (such as flavored milk and added-value drinking yogurts) to core staple products (like powdered milk and yogurt) representing key categories.

Europe

Consumer knowledge, perception and purchasing behaviour of dairy products vary from country to country. A recent study on consumer perceptions of milk fat in several countries (Denmark, the UK, and the US) reported that awareness of milk saturated fat was higher among respondents from the UK (53%) than from Denmark (44%) and the US (38%; Vargas-Bello-Pérez et al., 2020). Milk fat was perceived as healthy in all 3 countries and whole and semi-skim milk were less consumed in Denmark (20 and 36%, respectively) compared with the UK (50 and 49%, respectively) and the US (47 and 50%, respectively).

In the UK, the consumption of liquid milk between 1970 and 2000 has shifted, with a decline in whole milk consumption and a rise in semi-skimmed and skimmed milk consumption (Kliem & Givens, 2011; DEFRA 2022). This trend has been mirrored in other countries such as France, Denmark, Italy and Germany (Kliem & Givens, 2011). The cause of the decline in whole milk consumption (and consumption of other dairy products) can be partially attributed to the surge in popularity of plant-based milk alternatives, as well as increased consumer awareness of sources of saturated fat in their diet following publication of the UK Food Standards Agency's report on "Saturated Fat and Energy Intake" (Food Standards Agency, 2008). It is important to note that it is too early to establish the real relevance plant-based milk alternatives versus milk, even though their popularity seems to be grown.

In Spain, cow milk dominates the market while goat milk consumption is growing due to its perceived health benefits. However, semi-skimmed cow milk is preferred by Spanish consumers, followed by skimmed and whole milk (Collantes, 2021). Notably, overall liquid milk consumption has decreased by 7% since 2008. Meanwhile, lactose-free milk is gaining popularity, while demand for milk enriched with calcium, vitamin D or omega-3 FA is declining. Concerns around dairy farm profitability and sustainability, animal welfare, and rural depopulation have led to promotional efforts by industry organizations (e.g. InLac; Interprofessional Dairy Organization, and FeNIL; National Federation of Dairy Industries), and research has focused on promoting the benefits of dairy fat intake (López & Lainez, 2022). Plant-based drink consumption has increased significantly, however there is still a lot of misinformation regarding nutritional facts (Iglesias & Andrés, 2022).

In Finland, the numbers of dairy production factories as well as milk producers have decreased markedly in 20 years. Also, milk consumption has dropped in this country from 227.6 kg per capita in 1970 to 99.2 kg per capita in 2021, with a shift towards skimmed and semi-skimmed milk (NRIF, 2022). The consumption of butter has decreased since 1962, while the consumption of cheese has increased. Also, yogurt consumption has risen while sour milk consumption has fallen (NRIF, 2022). There has been a long-standing debate surrounding dietary saturated fats and their impact on cardiovascular diseases (CVDs) (Puska & Jaini, 2020) and finally The National Nutrition Council of Finland supported policies promoting low-SFA dairy products (Jallinoja et al., 2016). Recently a study, which investigated Finnish consumers' willingness to pay with 320 participants, showed that Finnish consumers prefer low-price butter derived from milk produced by cows fed with regular feed that carries the 'Carbon Trust' label, and it is labeled with the claim 'Reduced saturated fat', which were aspects related health and environmental-friendly, respectively (Asioli et al., 2023). In addition, one-third of these participants were willing to pay a premium price for the new type of butter (butter derived from milk produced by cows fed with rapeseed feed) (Asioli et al., 2023). Notably, Finnish consumers increasingly favor plant-derived beverage and vegetable products over dairy products (Jallinoja et al., 2016).

Examples from Africa and Asia

In Egypt, milk fat content determines the price of milk, with a basic milk price assigned to 3% fat content (Soliman and Mashhour, 2011). Historically, whole milk consumption has exceeded that of low-fat or de-

fatted (skim) milk in Egypt. However, a gradual increase in the demand for fat-reduced milk has been observed in recent years, followed by a renewed upsurge in the preference for whole milk (Soliman and Mashhour, 2011). Egyptian consumers perceive dairy products as a source of health benefits, however rising prices have altered preferences. Yogurts, sour milk, soft and hard cheeses, liquid milk, and butter are the most consumed dairy products. Margarine has become more popular as butter prices rise (EU, 2019). Recently, consumers have become increasingly interested in the FA composition of milk, particularly CLA and omega-3 FAs, however, high costs hinder the market's growth. The low-income consumers still prioritize affordability, which may include products with high TFAs (El-Hossainy et al., 2021). Plant-based and non-dairy beverage products are increasing in the Egyptian markets, however, the shift towards these products is still weak and needs more emphasis on their nutritive value (El-Hossainy et al., 2021).

In China, dairy production reached 30.55 million tons in 2023, with liquid milk making up over 90%. Demand for dairy products is still increasing with per capita consumption reaching 14.4 kg in 2021, a 10.6% annual increase (Song, et al., 2022). China's dairy market offers various products, including liquid milk, milk powder, condensed milk, and cheese. Liquid milk (with over 13 subcategories) dominates the market and growing consumer demand reached a per capita consumption of 14.4 kg in 2021. Higher-income consumers prioritize nutrition, taste, price, sales channels, and packaging when purchasing dairy products (Yang et al., 2021). Despite the growth, China's dairy consumption falls behind developed countries. At present, lipid-optimized products attract consumers, especially those labeled "grass feed" or "grazing".

In Bangladesh, milk processors use a payment system based on milk fat percentage (Karmaker et al., 2020). The Bangladesh Standards and Testing Institution (BSTI) sets minimum legal requirements for milk fat in the market (Hossain et al., 2022). Research on milk and dairy products in Bangladesh primarily focuses on total fat content. The consumption of liquid milk has greatly been challenged by different soft and energy drinks. The purchasing capacity of the individuals is another concern, especially the allocation of family budget for dairy items are not sufficient. Also, adulteration, including watering milk, skimming milk, and adding low-cost animal and/or vegetable fat and/or oil to milk (or synthetic milk), is a customer concern (Hossain et al. 2022).

Oceania

Dairy production in New Zealand has historically oriented towards export markets (Aziz et al., 2019). Approximately 95% of the milk produced in New Zealand is earmarked for export, accounting for around a third of the volume traded. Notably, New Zealanders are among the highest per capita consumers of milk (~110 kg milk p.a.) and butter (~6 kg p.a.) (NZPC, 2020). So, New Zealand's dairy industry conducts research on milk fat to meet consumer demands and preferences abroad in export-oriented countries (Aziz et al., 2019; Galtry, 2013), focusing on the impact of pasture feeding on its quality. Grazed pasture is the primary feed source for cows resulting in a series of studies focused on understanding the seasonal variability of milk fat composition. Feeding grain can alter the flavor profile of the milk, and studies have identified specific compounds responsible for "grassy" notes associated with pasture feeding (Aziz et al.,

2019). Studies have identified compounds responsible for distinct flavors and aromas, enabling the optimization of milk and dairy products for international markets sold (Bendall, 2001; Wales & Kolver, 2017).

Studies covering consumer perception of milk fat

Consumer perception of milk fat has been extensively studied to understand its impact on purchasing decisions and dietary preferences (Martínez-Padilla et al., 2023; Vargas-Bello-Pérez et al., 2020). Studies consistently show that milk fat content significantly influences the taste and flavor perception of dairy products. Higher fat content often correlates with a richer, creamier taste, which many consumers find more satisfying and enjoyable (Waldron et al., 2020). Milk fat contributes to the smoothness and mouth-coating texture of dairy products like milk, yogurt, and ice cream. Consumers often associate higher fat content with a more indulgent and pleasant mouth feel (Waldron et al., 2020). Consumer attitudes towards milk fat have evolved with changing dietary guidelines and health trends. While some consumers prioritize low-fat or skim milk due to perceived health benefits (lower calorie and fat content), others view whole milk and full-fat dairy products as more natural and less processed (Vargas-Bello-Pérez et al., 2020).

There is ongoing debate and varying consumer beliefs regarding the nutritional benefits of different milk fat levels. Some consumers prefer higher fat content for its perceived satiety and nutritional value (fat-soluble vitamins and essential fatty acids), while others opt for lower fat content for weight management or cardiovascular health reasons (McCarthy et al., 2017). Milk fat content influences culinary practices and recipes. Chefs and home cooks often choose specific fat levels for cooking, baking, and preparing dishes based on desired texture, flavor extraction, and cooking techniques (Marcus, 2013). Consumer perception of milk fat is also shaped by labeling and marketing strategies. Clear labeling indicating fat content (e.g., whole milk, 2% milk, skim milk) helps consumers make informed choices based on their preferences and dietary goals (Hoque et al., 2018). Consumer perception of milk fat can vary significantly across regions and cultures. Some cultures traditionally favor higher-fat dairy products for their culinary heritage and cultural preferences (Vargas-Bello-Pérez et al., 2022). Over time, there have been shifts in consumer preferences towards reduced-fat or fat-free dairy products driven by health consciousness and dietary trends. However, there remains a steady consumer demand for whole milk and full-fat dairy products based on taste, texture, and perceived nutritional benefits (Kumari et al., 2022).

Integrating these studies provides a comprehensive understanding of how consumer perception of milk fat influences purchasing decisions, dietary choices, and overall satisfaction with dairy products. This knowledge is valuable for dairy industry stakeholders in product development, marketing strategies, and meeting consumer preferences effectively. The authors of this reflection believe that consumer knowledge, perception, and purchasing behavior vary across countries and regions, influenced by factors such as cultural background, income level, and nutritional awareness. We note that in developed countries (especially in North America and Europe) there is a shift in consumer preferences towards low-fat milk, skim milk, and plant-based drink options. This trend is driven by concerns about saturated fat intake and animal welfare beside the window dressing of non-dairy beverages. On the other hand, in developing

countries (especially Africa and some parts of Asia) where affordability is a priority, dairy products remain popular. We also stress the need for dairy industries to address emerging trends and consumer concerns, such as sustainability, animal welfare, and nutritional value, to maintain their competitive edge in the market.

Milk fat from an industrial perspective

Milk fat plays a crucial role in the dairy industry for several reasons (Waldron et al., 2020). Milk fat contributes significantly to the flavor and texture of dairy products, and it provides richness and enhances the overall sensory experience of dairy products. Milk fat is important for processing flexibility allowing the manufacture of different products based on fat percentages and contributes to the texture, meltability, and overall performance (Chandan, 2015) during processing and storage. Also, milk fat content influences the economic value of milk as higher-fat milk commands a premium price in the market, which is beneficial for dairy farmers and processors (Wiley, 2007). The following paragraphs will explain specific details about the dairy industry from different geographical regions.

North America

Milk fat has become valuable in the US dairy market, making up more than 50% of the price paid to milk producers (Santos & De Vries, 2019). Following a consumer shift towards healthier, sustainable, and ethically sourced products, the industry has developed novel technologies such as lactose-reduced and lactose-free milk variants. More recently, a novel approach combining partial lactose removal through ultrafiltration with enzymatic hydrolysis of the remaining lactose has yielded a lower-calorie, lactose-reduced fluid milk product (Barbano, 2017). In Mexico, milk is segmented according to fat content (whole, semi-skimmed, and skimmed milk) but few efforts have been made to introduce more novel milk types. In North America, the North American Free Trade Agreement (NAFTA) regulates the production of dairy products that can be exported or imported (Kondaridze and Luckstead, 2023). However, each country such as the United States, Mexico, and Canada has an economic system and a consumer culture that allows the production of certain variants in the dairy supply in the market of these countries.

Europe

In the UK, the launch of the “Saturated Fat and Energy Intake” program in 2008, led to growing industry interest in improving the FA profile of milk and dairy products by dietary alteration (Dairy4future, 2021). One product arising from research following this was whole milk containing less SFA, but it is no longer commercially available. There have been other efforts by the UK industry to meet consumer demand in terms of milk fat composition. Two products with enhanced long-chain omega-3 PUFA contents (achieved by either fortifying fresh milk with fish oil emulsion or adding fish oil to dairy cow diets) were launched in 2005, but again these are no longer commercially available, perhaps partially due to the higher production costs for these products.

The dairy industry in Spain has absorbed all the increase in domestic milk production, so that in the last decade the volume of milk processed has increased by 1.3 million tons. More than half of this increase went to cheese production and the rest to yogurts, desserts, and industrial products, compared to stabilization in packaged liquid milk. Changes in the business structure have occurred, thanks to the growth of medium-sized dairy industries that are committed to more sustainable production systems and good animal welfare practices (López & Lainez, 2022).

The Italian dairy industry, specifically the fluid milk sector, has undergone considerable changes over the past few decades. However, 60%-80% of national milk yield is used for cheese making with high added value. The pursuit of liberalization is not a novel phenomenon within the EU, and the 2003 Reform, largely prompted farm-gate competitiveness, and created a more market-driven industry, leading to intense competition and profit redistribution along the supply chain (Cassandro, 2003).

Currently, Finnish dairy market offers fat-modified products, especially butter-vegetable oil mixtures, using different vegetable oils such as rapeseed, olive, and linseed. Carbon-neutral and animal welfare-friendly practices are increasingly important, with dairy companies paying more for farmers committed to animal welfare. Dairy companies market their products as free-range (loose housing, year-round access to outdoors and grazing during summertime), increased animal health, soy-free, and GMO-free feeding, and organic labeling. Finnish dairy companies have expanded into plant-based drinks and other plant-based dairy-like products. In addition, in recent years high-protein and sugar-reduced dairy products have become more important in the market.

Although in the European Union, there are certain common laws for the member countries, the dairy industry in each country works based on what their economic system allows them as well as the culture of dairy consumption that exists in each country.

Examples from Africa and Asia

The dairy industry is a key component of Egypt's food system. The government highly supports the dairy industry via legalization and financial support (Soliman & Mashhour, 2011). In addition to government support, the Chamber of Food Industries, operating under the auspices of the Federation of Egyptian Industries, acts as a prominent entity advocating for the interests of the dairy industry. Furthermore, research institutions and universities collaborate closely with the industry, offering consultancy services and addressing challenges faced by this sector.

In China, the dairy industry is increasingly emphasizing the development of functional dairy products and catering to diverse age groups. Functional dairy products are made by precisely adding functional ingredients to raw milk. Examples include high-end products with deep-sea fish oil and phospholipids (for improving bone- and cardiovascular- health in older adults) and with algal oil DHA, vitamin A, and vitamin D to promote healthy growth and development in children. Ongoing research and development efforts continue to drive innovation in this area towards “zero sugar”, high fiber, probiotics, and special contributions + organic milk powder addressing lactose intolerance (Wang et al., 2021).

Milk production in Bangladesh falls short of meeting demand, leading funding agencies to support initiatives that boost output. However, funding is limited, and the industry doesn't invest enough in research addressing challenges and the scenario needs to be changed. In addition, the use of non-dairy beverages (i.e. soy milk and coconut milk) to replace/be used along with milk has yet to reach the industry (Hossain et al., 2022). Dairy farmers receive higher payments for more fat. Adulteration and fat losses during the handling and processing of milk are major concerns.

The cases of Africa (Clay and Yurco, 2020) and Asia (Zolin et al., 2021) each deserve a thorough review, however in these regions of the world it is necessary to consider geopolitical situations and agronomic conditions that can greatly limit or promote the development of the dairy industry.

Oceania

In recent years, the New Zealand dairy industry has focused on the development of premium products for consumers in Asian countries, particularly in China, with the narrative of naturalness in pastoral production (Galtry, 2013). New Zealand milk sector is incorporated into infant formula, and the research in milk fat has focused on the role of some milk fat components, namely phospholipids (sphingomyelin, gangliosides, ceramides, and milk fat globule proteins) as key for the neural development of infants (Aziz et al., 2019; Galtry, 2013). Dairy ingredients such as SureStartTM have been developed for use in pediatric formulas to support cognitive function. These ingredients seek to increase the concentration of phospholipids in infant formula to levels comparable to those found in human breast milk.

The dairy industry has been adapting to cope with changing consumer preferences, with a focus on developing lower-calorie, lower-fat, and more sustainable products. These adaptations have gained momentum in some countries resulting in dairy products that are well-received by the consumer. In North America, innovative products such as lactose-reduced and lactose-free milk variants have emerged, while in Europe, fat-modified and FA-improved products have been developed. All these advancements have prioritized environmentally friendly and animal welfare-friendly practices. However, in countries where the primary focus of industry is maximizing production without concern for environmental impact and health benefits, it is unrealistic to expect swift changes and conform to worldwide trends owing to various cultural, economical, and political issues.

Milk fat from an academic perspective

North America

The success of current and future initiatives aimed at promoting the consumption of dairy products will, in part, rely on the public's perception of their potential health benefits. Recent research has shifted its focus from modifying milk FA profiles to investigating the effects of other milk fat components on human health, particularly bovine milk fat globule membranes (MFGM). Several reviews have emphasized critical aspects of MFGM, including its role in brain-immune-gut axis development in early life; fat digestion during infancy, and milk fat droplet size regulation and implications for digestion (Yao et al.,

2023). In addition to advancing our understanding of milk fat synthesis mechanisms, there is a need to bridge the gap between animal science and dairy food science to develop practical applications for human nutrition. In Mexico, for the past 15 years research on milk FA has been divided into humans (Escalante-Araiza et al., 2021), animals (especially ruminants; Vargas-Bello-Pérez et al., 2020), and dairy products (Ochoa-Flores et al., 2021). Funding bodies have been interested in supporting research initiatives focused on milk fat or any other milk bioactive compound but today most research funding (National Council of Humanities, Sciences, and Technologies; CONAHCYT) supports those projects with the social application.

Europe

Within the UK, The Scientific Advisory Committee on Nutrition (SACN) recommends limiting SFA to 10% of total energy intake and TFA to 2%. However, adult's intake of SFA remains higher than the SACN recommendation (SACN, 2019). The impact of modified FA dairy products on human health was recently determined via a randomized controlled trial at the University of Reading ("Replacement of SFAs in dairy on Total cholesterol, RESET), during which SFAs in milk, cheese, and butter were replaced with cis-monounsaturated fatty acids (cis-MUFAs) by changing the dairy cow diet. The study reported improved blood lipid profiles, vascular function, and reduced cardiovascular disease (CVD) risk markers (Vasilipoulou et al., 2020). Also, there is still enduring research on the n-3 PUFA content of milk fat, especially for organic milk. However, it should be remembered that even the n-3 PUFA content of organic milk is still very low compared with other sources of dietary n-3 PUFA, and it is still debatable whether this would be nutritionally meaningful if all consumers switched from conventionally- to organically-produced milk. It should also be considered that the majority of n-3 PUFA in milk is in the form of α-linolenic acid (ALNA), rather than the biologically active longer chain n-3 PUFA EPA and DHA.

Numerous large-scale nutritional studies conducted in Spain, specifically the Predimed and Predimed Plus, have investigated the relationship between dairy product consumption and cognitive function within the context of the Mediterranean diet and the results showed no clear prospective associations between consumption of most consumed dairy products and cognition (Ni et al., 2022). Also, along these lines, recent research aimed at incorporating MFGM into different dairy products is providing promising results in the prevention of age-associated cognitive decline (Calvo et al., 2023).

Italy is a leader in research on the FA profile of small ruminant dairy products ranging from FA characterization of cheeses to the use of FA as biomarkers for production seasons (Formaggioni et al., 2020). In contrast, research on milk fat modification in Finland has been limited and mostly focused on mitigating enteric methane emissions and modulating milk fat depression in early lactation (Jallinoja et al., 2016).

Examples from Africa and Asia

Enhancing and optimizing milk fat and its FA profile has garnered significant attention in Egyptian research institutions and universities. Notably, there has been a greater focus on augmenting fat and

healthy FA content in comparison to other milk constituents, such as protein. This may be attributed to the possibility of affecting milk fat content/composition through many strategies including animal nutrition and genetic improvement (Soliman & Mashhour, 2011).

In China, precision nutrition is a common issue faced by researchers in the field of dairy farming, such as the dietary addition of 5% rumen-protected polyunsaturated fatty acids (sesame oil) increased the content of UFA, MUFA, and CLA in milk (Xu et al., 2022). Whereas the research in the milk processing field focuses on optimizing milk fat quality, including altering inherent lipid components, and adding exogenous lipids (Song et al., 2022). In terms of basic scientific research on milk fat, the National Natural Science Foundation of China (NSFC) has largely funded the research exploring the mechanism of nutritional regulation of milk fat synthesis, milk fat depression syndrome, and infant milk fat digestion. Today, Bangladesh is very active in characterizing FA from different dairy products such as cheese, butter, ghee, doi, and rasomalai from buffalo (Asif et al., 2021). This is perhaps one of the leading countries in using these ruminants focused on dairy production.

Oceania

There is a great trend for searching the effects of milk phospholipids on cognitive development in infants, as well as exploring their potential to address brain function decline in adulthood. Other research interests include the development of 'nutrient bundles' based on milk phospholipids and enriched with other nutrients such as vitamins to deliver benefits on cognition, mood, and sight (da Silva et al., 2021; Yao et al., 2023). Furthermore, research has also been conducted to characterize the composition of MFGM ingredients (Brink et al. 2020), providing a deeper understanding of the complex chemical entities present in milk phospholipids, informing animals and clinical trials.

Author Insights

Modifying milk fat composition has shown promise in improving blood lipid profiles, and vascular function and reducing cardiovascular disease risk markers. Research on milk fat modification has primarily focused on enhancing the nutritional value of dairy products for human health, rather than addressing environmental concerns. There is a need for more research on the practical applications of milk fat modification in human nutrition, as well as bridging the gap between animal science and dairy food science.

Implications for the dairy industry

As a result of this review, it is clear that milk fat has been and continues to be important for the dairy industry, not only for the development of different dairy products but also as a factor that promotes economic gains for both farmers and different actors in the chain of dairy production. The dairy industry has been very receptive to the needs and demands of consumers and this is reflected in the development of products that are even made with alternative inputs to milk (for example non-dairy drinks made from oilseed seeds).

Perhaps for the industry, the scientific development related to the improvement of fatty acids in milk fat is not a priority, but the total amount of milk fat is since it is important for the processing and manufacturing of different products. The dairy industry is likely to continue searching for alternatives to dairy fat that may have similar sensory and processing characteristics. However, along with this, the dairy industry will have to do a lot of work around water and pollution management (i.e., Shine et al., 2020). Society, as well as governments, have more demands and the dairy industry is no exception in its responsibility in the face of global warming. Therefore, in the immediate future, the carbon footprint and chemical elements will be a big issue that the industry will have to take care of.

Prospective opportunities for the future

Currently, the intensity of scientific research into milk fat (and strategies to change it) is perhaps not as high as it once was, due to different phenomena which vary depending on geographical location. As highlighted earlier in this opinion paper, support for research on milk fat depends on the market, consumer expectations/awareness, and productive priorities, and until now this has focused on the development of milk enriched in bio-functional FA. Recently, non-dairy products have taken more market positions in many countries, but their prices as well as the long-term effects of their consumption seem to prevent their macro spread.

Regarding current and near-future research interests related to milk fat, efforts appear to be shifting away from trying to manipulate the concentration of individuals/groups of FAs within milk fat. Instead, there is a growing body of evidence suggesting that despite the typical FA profile of milk fat, higher dairy intake has a neutral or protective effect on cardiometabolic health risk factors, compared with lower intakes (Poppitt, 2020), possibly due to other beneficial components of milk. Recent research suggests that different dairy products may differentially affect these risk factors, leading to the concept of a “matrix effect”, which has been supported by both animal and human (Mohan et al., 2021) studies. The matrix effect is primarily attributed to hard cheeses vs other dairy products, where the physico-chemical properties of the cheese are believed to limit lipid absorption in the gastrointestinal tract. Several mechanisms have been suggested to explain this phenomenon, including the formation of calcium soaps of FAs in the small intestine leading to increased fecal fat excretion (Yao et al., 2023; Brink et al., 2020). Elucidation of the underlying mechanism remains a continued research interest for both researchers and industry professionals with potentially far-reaching implications for milk production, dairy processing, and human health outcomes.

Other near-future priorities may involve investigating the role of additional bioactive lipid structures present in milk. Milk fat is compartmentalized into milk fat globules, consisting of a predominantly triglyceride (TAG) core surrounded by a triple-layer milk fat globule membrane rich in phospholipids, including sphingolipids. These lipids have been reported to inhibit fat absorption, neutralize bacterial endotoxins, and have anti-inflammatory and anti-pathogen action in rodent models (Yao et al., 2023). Following milk processing and the disruption of the milk fat globule, these lipids tend to be enriched in aqueous fractions such as buttermilk, serum, and whey (da Silva et al., 2021). The fascination with augmenting and isolating milk phospholipids endures, underpinned by the diverse health benefits

correlated with these MFGM constituents. Further research is necessary to elucidate the impacts of temperature, shear, and pressure on the structural chemistry and stability of milk fat under diverse processing conditions. Moreover, modulating milk FA profiles via dietary manipulations, genetic selection, and regulation of gene expression present opportunities. This research reflection did not consider Sout America, and further attention must be given to this region as it plays a significant role in the dairy industry, both as a producer and exporter of dairy products. While countries in this region may not always be top-of-mind when discussing dairy, their impact on international markets cannot be overlooked. Here are some key points highlighting South America's influence on the global dairy industry. South American countries, particularly Argentina, Brazil, and Uruguay, are major producers of dairy products, including milk, cheese, and butter. These countries have sizable dairy industries with modern production facilities and large-scale dairy farms, favorable climate conditions for dairy farming, and competitive production costs, allowing them to supply dairy products to various regions around the world. South American dairy exports play a crucial role in the worldwide dairy trade dynamics. They contribute to meeting the demand for dairy products in regions where production may be limited or seasonal, thus helping stabilize international dairy prices and supply.

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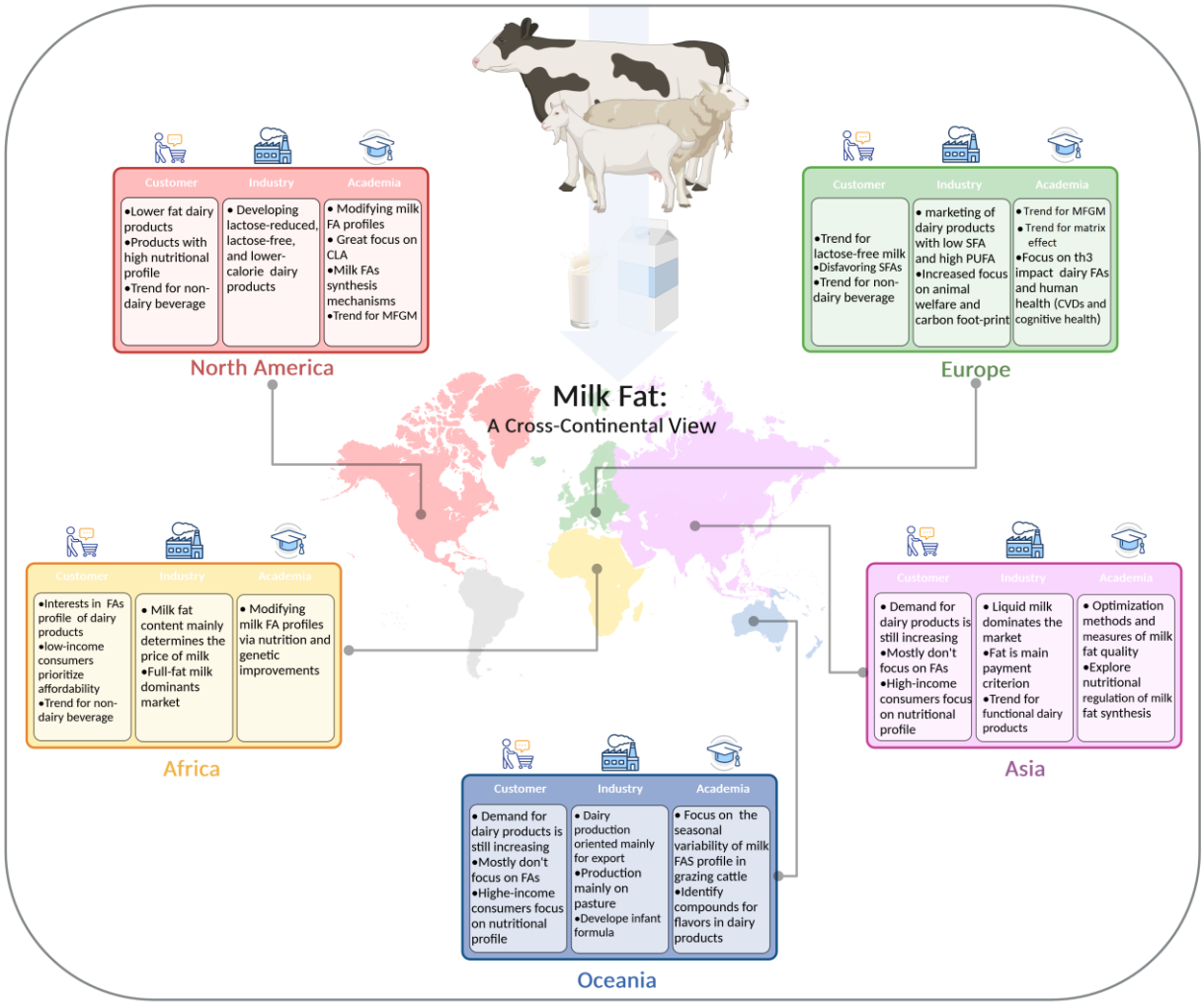

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637 **Figure 1.** Milk Fat: a cross-continental view (Created with BioRender.com).

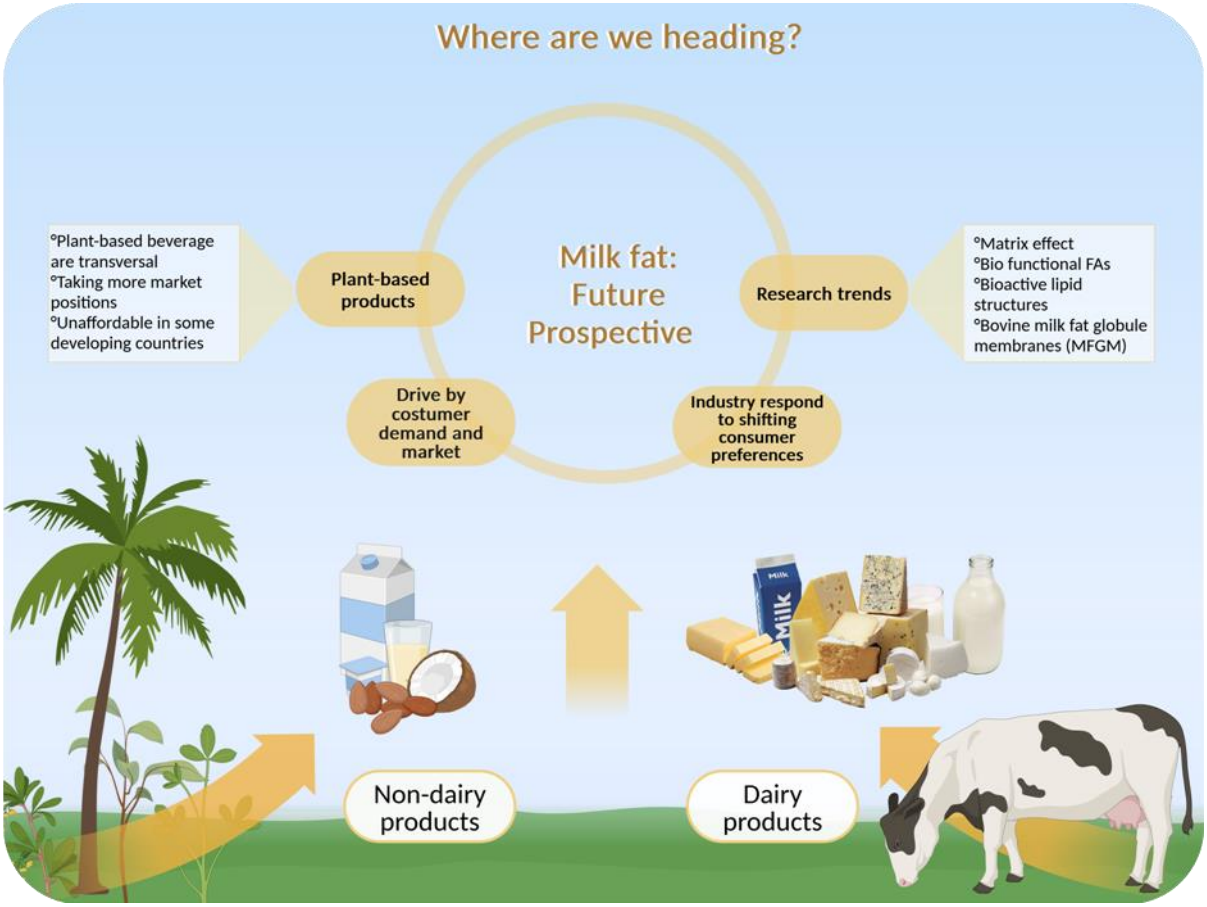

Figure 2. Milk Fat: prospective opportunities for future (Created with BioRender.com).