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A REVIEW EXPLORING THE INCORPORATION OF MICROALGAE TO ENHANCE THE NUTRITIONAL PROFILE AND HEALTH BENEFITS OF DAIRY PRODUCTS

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ABSTRACT

Microalgae have gained significant attention in the food industry as a valuable source of bioactive compounds and functional ingredients. Their incorporation in dairy products offers promising opportunities for the development of innovative and healthier dairy products. This review highlights the potential benefits and applications of microalgal biomass and its derivatives in various dairy products, including milk, yogurt, cheese, ice cream, and other dairy-based products. The addition of microalgal biomass to dairy products can enhance their nutritional profile by providing essential nutrients such as proteins, omega-3 fatty acids, vitamins, minerals, and antioxidants. Microalgae are known for their high protein content, and their inclusion in dairy products can contribute to increased protein levels, making them a suitable option for protein enrichment in dairy-based formulations. Moreover, microalgae-derived omega-3 fatty acids, such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), offer potential health benefits, including cardiovascular and cognitive health. Furthermore, microalgae exhibit functional properties that can improve the texture, rheology, and stability of dairy products. The polysaccharides and proteins present in microalgae contribute to emulsification, foaming, and gelling properties, which are essential in product formulation and processing. Microalgae pigments can also provide natural colorants, reducing the need for artificial additives in dairy products. In addition to the nutritional and functional aspects, microalgae possess bioactive compounds with potential health-promoting properties. These include antioxidants, antimicrobial agents, and immunomodulatory substances, which can enhance the health benefits of dairy products. The incorporation of microalgae-derived bioactive compounds in dairy products may contribute to improved antioxidant activity, extended shelf life, and enhanced consumer appeal. Despite the numerous advantages, challenges exist in terms of flavor, aroma, and sensory acceptability when incorporating microalgal biomass into dairy products. The distinctive flavors and aromas associated with certain microalgae strains can affect the sensory characteristics of the final product. Therefore, optimization of the formulation, processing techniques, and masking strategies is essential to mitigate any undesirable sensory attributes. In conclusion, the addition of microalgae in dairy products offers exciting opportunities to develop innovative and healthier dairy formulations. The potential nutritional, functional, and bioactive properties of microalgae can contribute to the production of dairy products with improved nutritional profiles, enhanced functionality, and added health benefits. However, further research is needed to optimize the incorporation of microalgal biomass and its derivatives in dairy products while ensuring sensory acceptability, regulatory compliance, and consumer acceptance.

***Keywords*:** Dairy products, food nutrition, functional ingredients

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1. INTRODUCTION

Microalgae and their derivatives have gained increasing attention as potential ingredients in the development of innovative and sustainable food products. With their remarkable nutritional profile and bioactive compounds, microalgae offer promising opportunities for enhancing the nutritional value and functional properties of various food matrices. In recent years, the exploration of microalgae utilization in the dairy industry has emerged as an intriguing area of research. Dairy products are widely consumed and renowned for their excellent nutritional

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composition and health benefits (Fig. 1). However, there are growing concerns about the sustainability and health implications associated with conventional dairy production. As a result, there is a growing interest in finding alternative sources of ingredients that can provide similar nutritional benefits while addressing environmental and health-related challenges (Hernández et al. 2022).

Microalgae, being photosynthetic microorganisms, possess the unique ability to convert solar energy into valuable compounds, including proteins, essential fatty acids, vitamins, minerals, and antioxidants. These bioactive components make microalgae an attractive candidate for improving the nutritional content of dairy products. Furthermore, microalgae-derived compounds have been found to possess various health-promoting properties, such as anti-inflammatory, antioxidant, immunomodulatory, and hypo-cholesterolemic effects, which can further enhance the functional attributes of dairy products (Lu et al. 2019; Hernández et al. 2022; Khemiri et al. 2022; Verni et al. 2023).

The utilization of microalgae in dairy products offers several potential benefits. Firstly, incorporating microalgae-derived ingredients can increase the protein content of dairy products, making them more suitable for individuals seeking plant-based protein alternatives. Additionally, microalgae contain a wide range of essential fatty acids, including omega-3 fatty acids, which are known for their positive effects on cardiovascular health. By incorporating microalgae-derived fatty acids into dairy products, it is possible to enhance their nutritional profile and provide consumers with a more balanced fatty acid composition. Moreover, microalgae possess unique functional properties that can improve the texture, stability, and sensory attributes of dairy products. The polysaccharides and pigments present in microalgae can act as natural thickeners, emulsifiers, and colorants, offering potential solutions for improving the overall quality and sensory appeal of dairy formulations (Koyande et al. 2019; Nova et al. 2020; Khemiri et al. 2022; Kumar et al. 2022; Pan-utai and Iamtham 2023).

Despite the numerous potential benefits, the utilization of microalgae in dairy products is still in its early stages, and there are various challenges to overcome. These challenges include optimizing extraction techniques, ensuring safety and regulatory compliance, maintaining product stability, and addressing consumer acceptability and perception. This review aims to provide insights into the current research and developments in the utilization of microalgae and its derivatives in dairy products. By exploring the various applications, processing methods, and potential benefits, this review seeks to contribute to the understanding of the opportunities and challenges associated with incorporating microalgae into dairy formulations. Furthermore, this review will discuss the potential implications for product development, market trends, and the future prospects of microalgae-based ingredients in the dairy industry.

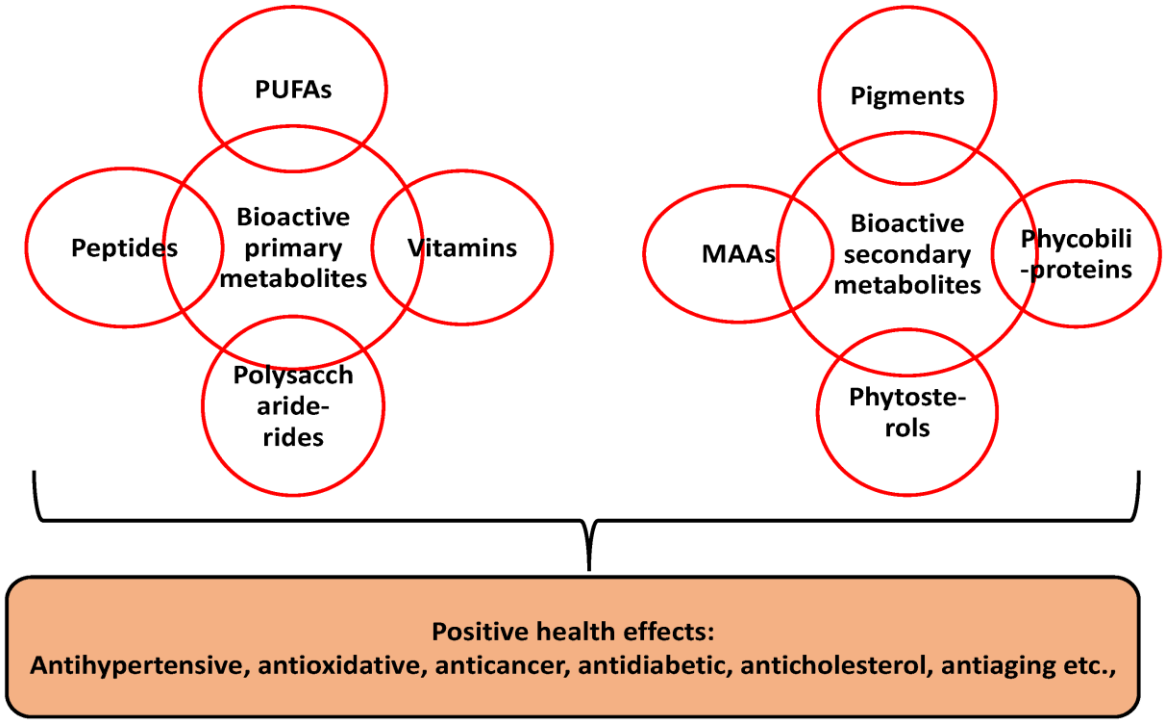

Fig. 1: Bioactive composition of microalgal biomass. PUFA—polyunsaturated fatty acids; MAAs—mycosporine-like amino acids (Ampofo and Abbey 2022).

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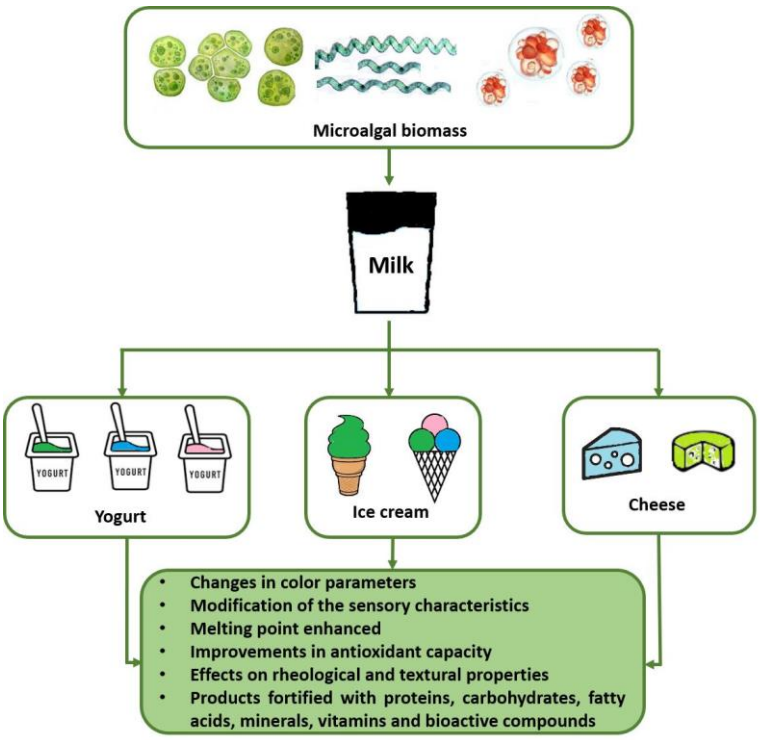

Fig. 2: Application of microalgae in dairy products. From milk, yogurt, ice cream, and cheese prepared, and various properties of the products are enhanced (Hernández et al. 2022).

2. Applications of Microalgal Biomass and Its Derivatives in Yogurt

Microalgal biomass and its derivatives have gained significant attention in various industries, including the food sector. One area of interest is their application in yogurt production (Fig. 2). Yogurt, a fermented milk product, is well-known for its probiotic properties and positive effects on human health. Incorporating microalgae into yogurt can not only enhance its nutritional profile but also offer additional functional benefits. This article will delve into the applications of microalgal biomass and its derivatives in yogurt, exploring their effects on physicochemical composition, color parameters, antioxidant properties, growth of starter and probiotic cultures, syneresis, texture, viscosity, and sensory properties (Nethravathy et al. 2019).

2.1. Changes in Physicochemical Composition of Yogurt

The addition of microalgal biomass, such as *Arthrospira platensis* (Spirulina), to yogurt formulations, has been studied. Microalgae are rich in proteins, and their incorporation into yogurt increases the protein content of the final product. For example, *A. platensis* has a protein content of around 70%. However, the addition of microalgae did not significantly affect the fat and carbohydrate content of yogurt. Furthermore, certain microalgae contain bioactive compounds, such as phycocyanin, which can be used as functional ingredients due to their therapeutic properties, including anti-cancer, anti-inflammatory, antioxidant, and nephroprotective effects. Phycocyanin also serves as a natural blue pigment, making it a potential alternative to artificial coloring agents in the food industry (Mohammadi-Gouraji et al. 2019).

2.2. Changes in Color Parameters of Yogurt

Incorporating microalgae into yogurt can influence its color properties. Microalgae, such as *A. platensis*, are rich in pigments like chlorophyll, carotenoids, and phycocyanin, which can impart distinct colors to the final product. For example, adding *A. platensis* can result in a shift from yellow to greenish hues in yogurt due to the high chlorophyll concentration. The stability of these colors may be influenced by factors such as acidity and pH. However, stabilization techniques, such as using anionic polysaccharides, can help maintain the color stability of microalgae-enriched yogurts (Barkallah et al. 2017).

2.3. Effect on Antioxidant Properties of Yogurt

Microalgae are known for their antioxidant properties, and their incorporation into yogurt can enhance its overall antioxidant capacity. Yogurts fortified with microalgal biomass have shown increased antioxidant activity

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compared to control yogurts without microalgae. This can be attributed to the presence of bioactive compounds, such as chlorophyll, carotenoids, and phycocyanin, in the microalgae biomass. These compounds help neutralize harmful free radicals and contribute to the health-promoting properties of the yogurt (Barkallah et al. 2017; Atallah et al. 2020; Kontogianni et al. 2021).

2.4. Changes in the Growth of Starter and Probiotic Cultures

The addition of microalgae to yogurt creates a favorable environment for the growth of microorganisms. Microalgae provide nutrients, such as exopolysaccharides, adenine, hypoxanthine, free amino acids, minerals, and vitamins, which support the growth and viability of lactic acid bacteria and probiotic cultures. Different species of microalgae have varying effects on the growth of starter and probiotic cultures in yogurt, depending on their nutrient composition and buffer capacity. The interaction between microalgae and milk proteins can also influence the buffer capacity and pH, affecting the viability and growth of probiotic microorganisms during fermentation (Beheshtipour et al. 2012).

2.5. Effects on Syneresis, Texture and Viscosity

Syneresis, texture, and viscosity are important characteristics of yogurt that affect its quality and consumer acceptance. The addition of microalgal biomass can impact these properties. Microalgae with high protein content, like *A. platensis*, can reduce syneresis, improving the stability of the yogurt product. The increase in protein concentration enhances the gel network and leads to firmer yogurt texture. However, the effect on texture can vary depending on the concentration and type of microalgae used. Apparent viscosity, which is influenced by factors such as starter cultures, handling, and the addition of stabilizers, can also be affected by the incorporation of microalgae (Felix da Silva et al. 2017; Aghajani et al. 2021; Barros de Medeiros et al. 2022).

2.6. Effect on Sensory Properties

The sensory attributes of yogurt, including taste, aroma, color, and overall acceptability, play a crucial role in consumer preference. The addition of microalgae and their derivatives to yogurt can introduce distinct flavors and aromas due to their aromatic compounds and pigments. Some microalgae, such as A. platensis, may impart a fishy taste or undesirable colors to yogurt, which can negatively impact consumer acceptance. To improve the sensory characteristics of microalgae-enriched yogurts, techniques like microencapsulation and flavor masking can be explored (Bchir et al. 2019; Salehi et al. 2021).

3. Applications of Microalgal Biomass and Its Derivatives

3.1. In Ice Cream

Ice cream is a popular frozen dessert enjoyed by people of all ages. It typically consists of a mixture of milk, sweeteners, stabilizers, emulsifiers, flavorings, and coloring agents. In recent years, there has been growing interest in using microalgal biomass and its derivatives as functional ingredients in ice cream production. Microalgae are photosynthetic microorganisms that can offer various benefits when incorporated into ice cream formulations. Here, we will explore the applications of microalgal biomass and its derivatives in ice cream and the potential effects on different aspects of the product (Durmaz et al. 2020; Wright 2021; Tiepo et al. 2021; Fig. 2).

3.1.1. Natural Colorants: Microalgae are rich sources of natural pigments, such as chlorophylls, carotenoids, and phycobiliproteins. These pigments can be used as natural colorants in ice cream, providing vibrant and attractive hues without the need for artificial coloring agents. For example, spirulina (*Arthrospira platensis*) is a microalga known for its blue-green color due to the presence of phycocyanin, a phycobiliprotein. Phycocyanin can be extracted from spirulina and used as a natural blue colorant in ice cream. Other microalgae, like *Porphyridium cruentum*, contain red pigments, such as phycoerythrin, which can be used to impart red or pink hues to ice cream. These natural colorants offer an alternative to synthetic dyes and can appeal to consumers seeking clean-label and natural products (Tiepo et al. 2021; da Silva Faresin et al. 2022).

3.1.2. Nutritional Enhancements: Microalgal biomass is nutrient-dense and can offer nutritional enhancements when added to ice cream. Spirulina, for instance, is known for its high protein content, containing all essential amino acids. By incorporating spirulina into ice cream, the protein content of the product can be increased, offering a potential source of protein for consumers. Additionally, microalgae contain various vitamins, minerals, and antioxidants, which can contribute to the nutritional profile of ice cream and provide potential health benefits (Marshall et al. 2003; Subhasri et al. 2022).

3.1.3. Functional Properties: Microalgal biomass and its derivatives can possess functional properties that can improve the texture, stability, and mouthfeel of ice cream. The polysaccharides present in some microalgae can act as natural stabilizers and emulsifiers, helping to prevent ice crystal formation and improve the overall stability of

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the product. These functional compounds can enhance the creaminess, smoothness, and mouth-coating properties of ice cream, resulting in a more enjoyable sensory experience (Durmaz et al. 2020).

3.1.4. Health Benefits: Microalgae are known to contain bioactive compounds with potential health benefits. For example, spirulina is rich in antioxidants, such as phycocyanin, which exhibits antioxidant and anti-inflammatory properties. By incorporating spirulina or other antioxidant-rich microalgae into ice cream, the antioxidant capacity of the product can be enhanced. These antioxidants may help to reduce oxidative stress in the body and contribute to overall health and well-being (Robinson 2014; Basheer et al. 2020; Kargın and Bilgüven 2022; Yousefi et al. 2023).

3.1.5. Sustainability: Microalgae are considered a sustainable ingredient option due to their ability to grow rapidly and their potential for cultivation in various environments, including non-arable land and wastewater. The production of microalgal biomass for ice cream production can have a lower environmental footprint compared to traditional agricultural crops. The utilization of microalgae in ice cream aligns with the growing consumer demand for sustainable and environmentally friendly food options (Durmaz et al. 2020). Incorporating microalgal biomass and its derivatives into ice cream formulations presents opportunities for product innovation and the development of healthier and more sustainable frozen desserts. However, it is important to consider factors such as taste, aroma, and consumer acceptance when using microalgae in ice cream, as some microalgae can have distinct flavors or odors that may need to be addressed. Further research and development are needed to optimize the concentration, processing methods, and sensory attributes of microalgae-enhanced ice cream to ensure consumer satisfaction and market acceptance (Robinson 2014).

3.2. Applications of Microalgal Biomass in Cheese

Microalgal biomass has gained attention as a potential ingredient in cheese production due to its nutritional composition, functional properties, and potential health benefits. The incorporation of microalgal biomass in cheeses can enhance their sensory, nutritional, and functional characteristics. Here, we will explore the applications of microalgal biomass in cheeses and discuss its effects on various aspects of cheese production (Cosentino et al. 2016; Till et al. 2019; Pandey et al. 2020; Garrido et al. 2020).

3.2.1. Nutritional Enhancement: Microalgae are known for their high nutritional value, containing essential amino acids, vitamins, minerals, and bioactive compounds. Incorporating microalgal biomass in cheeses can contribute to their nutritional profile by increasing protein content, enhancing fatty acid composition, and providing additional vitamins and antioxidants. For example, microalgae such as Chlorella vulgaris and *Arthrospira platensis* (spirulina) are rich in proteins and essential amino acids, making them suitable candidates for protein fortification in cheese. These proteins can improve the amino acid balance and increase the overall protein content of the cheese (Cunha et al. 2010).

3.2.2. Functional Properties: Microalgal biomass possesses functional properties that can benefit cheese production. The polysaccharides, fibers, and bioactive compounds present in microalgae can act as texture modifiers, emulsifiers, and stabilizers in cheese formulations. The incorporation of microalgal biomass can improve the rheological properties, water-holding capacity, and emulsifying ability of cheese, leading to desirable texture and enhanced reliability. Additionally, the presence of microalgal polysaccharides can contribute to the prebiotic potential of the cheese, promoting gut health (Golmakani et al. 2019).

3.2.3. Flavor and Aroma Enhancement: Microalgae contain various pigments and flavor compounds that can impart unique flavors and aromas to cheeses. The incorporation of microalgal biomass can introduce new sensory attributes, ranging from earthy and grassy notes to more distinct flavors like seaweed or marine flavors, depending on the microalgal species used. These flavor profiles can provide a novel taste experience and diversify the range of cheese flavors available to consumers (Mohamed et al. 2020; Wang et al. 2022; Raymundo et al. 2023).

3.2.4. Color Enhancement: Microalgal biomass can contribute natural colorants to cheeses, providing an alternative to synthetic colorants. The pigments present in microalgae, such as chlorophylls, carotenoids, and phycobiliproteins, can impart vibrant colors to the cheese, ranging from green to red or yellow, depending on the species used. These natural colorants offer an appealing visual aspect to the cheese, enhancing its aesthetic appeal and consumer perception (Awad et al. 2004; Till et al. 2019; Terpou et al. 2020).

3.2.5. Health Benefits: Microalgae are known for their potential health benefits, attributed to their rich content of bioactive compounds such as antioxidants, polyunsaturated fatty acids, and phytosterols. Incorporating microalgal

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biomass in cheeses can enhance their antioxidant capacity, promote cardiovascular health, and provide potential immune-modulatory effects. The bioactive compounds present in microalgae can contribute to the functional properties of the cheese and provide additional health-promoting properties to consumers (Hernández et al. 2022).

It is important to note that the successful incorporation of microalgal biomass in cheeses requires careful selection of microalgal species, dosage optimization, and proper processing techniques. The sensory attributes, dosage levels, and processing conditions must be carefully balanced to ensure the acceptance and palatability of the final product. Additionally, regulatory considerations and safety assessments should be conducted to ensure the suitability of microalgal biomass for cheese production (Hernández et al. 2022).

4. Use in Other Dairy Products

Certainly! In addition to the dairy products mentioned earlier, microalgal biomass and its derivatives have also been explored in other dairy products. Here are some examples:

4.1. Fermented Milk Products

Microalgal biomass has been studied in various fermented milk products, including kefir, buttermilk, and Labenah. Kefir enriched with microalgae such as *Arthrospira platensis* has shown increased protein content compared to the control samples. Similarly, the addition of microalgae to Labenah, a Middle Eastern product similar to cheese and yogurt, has resulted in higher protein content. The use of microalgal biomass in fermented milk products can enhance their nutritional profile and provide additional functional properties (Alizadeh Khaledabad et al. 2020; Hernández et al. 2022; Csatlos et al. 2023).

4.2. Fermented Milk Powder

Microalgae have been incorporated into reconstituted fermented milk powder. The addition of microalgae, such as A. platensis, in appropriate concentrations has shown a significant decrease in pH values during fermentation, indicating the influence of microalgae on the acidification process. Moreover, rheological studies have demonstrated changes in the flow index and consistency index in fermented milk powder fortified with microalgae (Martelli et al. 2020).

4.3. Fermented Beverages

Microalgal biomass has been used to fortify fermented beverages, such as buttermilk-based drinks. The incorporation of microalgae, such as A. platensis, at different concentrations has been studied, with acceptable acidity values observed at lower concentrations. However, higher concentrations of microalgae can lead to very high acidity levels. The addition of microalgae to fermented beverages can impact their flavor, nutritional composition, and overall quality (Nova et al. 2020; Ścieszka et al. 2021).

4.4. Other Dairy-Based Products

Microalgal biomass has been explored in a variety of other dairy products, such as spreads, dips, and processed cheeses. These applications aim to enhance the nutritional value, functional properties, and sensory characteristics of the products. The incorporation of microalgae can affect the physicochemical properties, texture, color, and antioxidant activity of these dairy-based products. It is important to note that the specific applications and effects of microalgal biomass in dairy products may vary depending on the microalgae species, concentration, processing methods, and other factors. Furthermore, regulatory considerations and guidelines should be followed when incorporating microalgal biomass or its derivatives into dairy products to ensure their safety and compliance with relevant regulations (Hernández et al. 2022).

5. Regulation Issues of Microalgal Biomass or Derivates in Dairy Products

The incorporation of microalgal biomass and its derivatives in dairy products is subject to regulation by various authorities around the world to ensure their safety and compliance with food standards. Regulatory bodies such as the European Food Safety Authority (EFSA), the Food and Drug Administration (FDA), the Food Safety and Standards Authority of India (FSSAI), and the Australia-New Zealand Food Authority (ANZFA) play a crucial role in setting guidelines and evaluating the use of novel ingredients in dairy products (Hernández et al. 2022).

In the European Union (EU), the use of microalgae as food ingredients is governed by EFSA regulation 258/97. According to this regulation, microalgae that were used as food ingredients prior to May 15, 1997, are not considered "novel food" or "novel ingredients." This means that microalgae species such as *Arthrospira platensis*, *Chlorella vulgaris*, *Chlorella luteoviridis*, and *Chlorella pyrenoidosa*, which have a history of use in food, can be added to dairy products without restrictions on their concentrations. The EU regulation also allows for nutritional claims related to microalgae's high protein content, as defined in regulation (EC) 1924/2006 (Regulation, 1997).

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EFSA has also evaluated the safety and use of specific microalgal derivatives in dairy products. For example, EFSA regulation 2017/2470 approves the incorporation of derivatives of Ettlia oleoabundans (formerly known as E. glacilis) and Ulkenia sp. in various food categories, including dairy products. Maximum levels for these derivatives are specified in the regulation, ensuring that their use remains within established safety limits (European Commission, 2017). In the United States, the FDA regulates the use of microalgal biomass and its derivatives in dairy products under the "Generally Recognized as Safe" (GRAS) designation. Manufacturers can submit GRAS notices to the FDA, providing scientific evidence demonstrating the safety of specific microalgal ingredients in food applications. Once a substance is recognized as GRAS, it can be added to foods, including dairy products, without specific approval from the FDA (Hernández et al. 2022).

Regulatory authorities worldwide typically impose maximum levels for the incorporation of microalgal biomass in dairy products to ensure safety and prevent excessive usage. These maximum levels vary depending on the regulatory body and the specific microalgae species or derivatives being used. However, it is worth noting that the maximum levels set by regulators for microalgal biomass in dairy products are often relatively low, usually not exceeding 2 grams per 100 grams of the product. The regulatory landscape for microalgal biomass in dairy products continues to evolve as scientific research advances and new applications emerge. Ongoing research and collaboration between regulatory authorities, industry stakeholders, and scientific experts are crucial for the development of clear and effective regulations that ensure the safety and promote the innovation of microalgal ingredients in dairy products (Hernández et al. 2022).

6. Conclusion

The incorporation of microalgae in dairy products presents a promising avenue for the development of innovative and healthier dairy formulations. The unique nutritional composition of microalgae, including high protein content, omega-3 fatty acids, vitamins, minerals, and antioxidants, offers opportunities for enriching dairy products with essential nutrients. These additions can enhance the nutritional profile of dairy products, providing consumers with added health benefits. Furthermore, microalgae bring functional properties to dairy products, contributing to improved texture, stability, and rheology. The polysaccharides and proteins present in microalgae play a crucial role in emulsification, foaming, and gelling, which are vital for product formulation and processing. Additionally, the vibrant pigments found in microalgae can act as natural colorants, reducing the need for artificial additives and enhancing the visual appeal of dairy products. Microalgae also contain bioactive compounds with potential health-promoting effects, including antioxidants, antimicrobial agents, and immunomodulatory substances. Incorporating these bioactive compounds into dairy products can enhance their antioxidant activity, extend shelf life, and offer additional health benefits to consumers. However, challenges exist in terms of flavor, aroma, and sensory acceptability when incorporating microalgae into dairy products. The distinct flavors and aromas associated with microalgae strains can impact the sensory characteristics of the final product. Careful formulation, processing techniques, and the use of masking strategies are essential to ensure that the addition of microalgae does not negatively affect the overall sensory experience. Regulatory considerations also play a role in the successful incorporation of microalgae in dairy products. Compliance with food regulations and obtaining approval for the use of microalgal ingredients is necessary to ensure product safety and consumer confidence. In conclusion, the addition of microalgae in dairy products holds great potential for the development of innovative and healthier dairy formulations. By harnessing the nutritional, functional, and bioactive properties of microalgae, dairy products can be enriched with essential nutrients, improved functionality, and additional health benefits. Further research and development efforts are needed to optimize formulation techniques, address sensory challenges, and ensure regulatory compliance to fully unlock the potential of microalgae in creating innovative and healthier dairy products.

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