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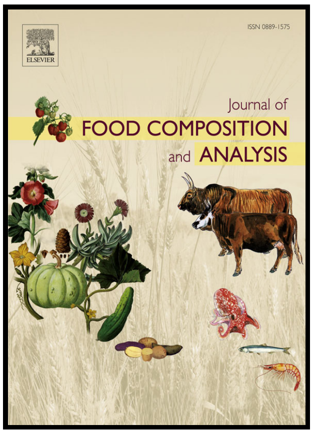

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Gabriela Kovaleski, Sónia P.M. Ventura

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Benefits, challenges and future of incorporation of algae into dairy products such as cheese and yogurt

Gabriela Kovaleski,[1] Sónia P.M. Ventura[1*]

[1]Department of Chemistry, CICECO – Aveiro Institute of Materials, University of Aveiro

Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

*Corresponding author:

Sónia P. M. Ventura, e-mail: spventura@ua.pt

Abstract

The development of new algae-fortified food products has grown steadily over recent years. Algae's nutritional value, along with their antioxidant properties, bioactive compounds, and natural pigments acting as colorants, are one of the key attractions for the food industry. Algae have gained attention in dairy products for their stable color, ability to enhance texture, and potential benefits in fermentation. This work systematically reviews the incorporation of microalgae and macroalgae into dairy products, specifically cheese and yogurt. The bibliometric analysis will examine the publication timeline, locations, and authorship of these studies, while the content analysis will focus on the parameters and compounds of interest in these dairy applications. Finally, this review will provide a critical perspective on the benefits of algae incorporation in dairy products, the challenges involved in their development, and future directions in this field.

Keywords: Microalgae, macroalgae, functional products, fortified food, dairy products

1. Brief Overview

The global demand for natural and fortified and/or functional products offering health benefits has been steadily increasing, appealing to both consumers and manufacturers (Matos et al., 2022). Algae are excellent sources of proteins, vitamins, minerals, fibers, and essential amino acids, all of which contribute to their antioxidant, antibacterial, anticancer, and anti-inflammatory properties (Lomartire et al., 2021; Yağmur et al., 2023; Radhakrishnan et al., 2017).

The use of algae in food has gained significant attention over the past five years in Europe, with applications in products such as ice cream, yogurt, cheese, spreads, pasta, beverages, bread, cookies, soups and sauces (Ampofo & Abbey, 2022; Boukid and Castellari, 2022). However, challenges remain in incorporating algae into food due to issues related to concentration balance, consumer acceptance, and nutritional quality (Nethravathy et al., 2019). High concentrations can enhance product quality but may also become unappealing to consumers due to undesirable changes in color and flavor (Tohamy et al., 2018). Additionally, the composition of each micro- or macroalgae varies, and their behavior can differ when added to various food products (Ampofo & Abbey, 2022). Moreover, the chemical composition of algae can be influenced by factors such as cultivation conditions, extraction and purification methods, as well as the accuracy of compound identification and quantification (Machu et al., 2015; Goiris et al., 2012; Kovaleski et al., 2022).

Dairy foods are rich in nutrients such as phosphorus, fat, calcium, proteins, and carbohydrates (Rizzoli and Biver, 2024). Yogurt is the best-known food consumed for centuries that provides probiotics (Hossain et al., 2024). Probiotics are live microorganisms that, when administered in adequate quantities, confer health benefits to the host. The bacteria *Lactobacillus* and *Bifidobacterium* are the best known. They have the benefits of improving the balance of the intestinal microbiota, preventing problems such as irritable bowel syndrome and diarrhoea; and strengthening the immune, endocrinological and neurological systems (Sánchez et al., 2016). Cheese is also a dairy food that provides health benefits and nutrients, which are influenced by the type of milk used, the manufacturing and maturation processes (López-Expósito et al., 2012). They are classified as fresh, soft, semi-hard, and hard cheeses. The main steps in cheese production are acidification, coagulation, and ripening. During acidification, fermentation occurs, where lactose is converted into lactic acid. Then, enzymes such as rennet can be added to coagulate the milk. In this process, casein, a milk protein, is precipitated, causing it to clump together and precipitate out of solution.

The addition of algae to dairy products has already been studied as a healthier product, because it has a natural coloring, high nutrient content and, in some cases, functional compounds. This systematic review analyzes the existing literature on cheese and yogurt fortified with algae.

2. Incorporation of algae in cheese and yogurt

The research publications reviewed in the present study were obtained from Scopus and Science Direct on March 1st to May 5th of 2024, using the following keywords: “Macroalgae+Yogurt”, “Microalgae+Yogurt”, “Macroalgae+Cheese”, “Microalgae+Cheese”, “Algae+Dairy Foods”, “Seaweed+Yogurt”, “Seaweed+Cheese” and “Seaweed+Dairy Foods”.

Considering a total of 614 articles found after this search, those not related to the topic, duplicates, and review articles were excluded, which resulted in 31 original manuscripts studying the incorporation of algae into yogurts and cheese. Figure 1 illustrates the structure of the work and outlines the research questions.

Figure 1.

The first article found on the subject was published in 2005, however, from 2017 onwards, the number of studies increased, with a considerable number of publications occurring between 2020 and 2023 (Figure 2).

Figure 2

3. Cheese

Eleven articles were found studying the incorporation of algae into cheeses (Table 1). The microalgae *Chlorella vulgaris* and *Spirulina* sp. were the most used in the studies, which is expected given their approval for use in food under the Novel Food Regulation (EU) 2015/2283. These species have been permitted for use as food in the EU since 1997 (Maritime Forum, 2024; CBI-2023). *Osmundea pinnatifida*, a red algae known by the common name pepper dulse, was the only macroalgae found. The concentrations of the added algae found ranged from 0.25 to 4% in lyophilized form. A variety of cheeses were studied, but for those passing through a fermentation in their production, algae were always added after. Unfermented cheeses such as spread cheese, brined cheese (matured in brine) and cheese analogue (mix of dairy or non-dairy fats or protein ingredients) and fermented cheeses such as Iranian and Kareish cheese (Feta-type cheese) and soft cheese were found.

Table 1.

3.1 Physicochemical composition

The most studied components were protein, fat, ash, carbohydrates and pH. They were compared by the algae used, since each alga has different compositions (Table 2). Faustino et al. (2023) were the first to study the incorporation of *Osmundea pinnatifida* in cheese and found that the amount of protein and carbohydrate increased after the algae addition, with the pH slightly decreasing from 5.95 to 5.61. The addition of the microalga *C. vulgaris* to different cheeses, brined and analogue cheese, increased the protein content (Yilmaz-Ersan et al., 2024). Mohamed et al. (2013) found that the incorporation of *C. vulgaris* at 1%, 2% and 3% increased the protein and carbohydrates contents, however, lipids, ash and pH decreased. Yilmaz-Ersan et al. (2024) achieved a good increase in protein by adding only 1% of *C. vulgaris* and there was also a decrease in lipids. Also with *C. vulgaris*, Tohamy et al. (2018) found a small increase in protein even with 4% of algae added, but unlike the others, there was an increase in lipids, carbohydrates and pH. The increase in protein was already expected since *C. vulgaris* contains approximately 55% protein (Radhakrishnan et al., 2017).

Yilmaz-Ersan et al. (2024) also studied cheese with 1% of *S. platensis* and found the same result obtained by the incorporation of *C. vulgaris* (high amount of protein and low amount of lipids). Agustini et al. (2016) studied *S. platensis* with 1% and 2% (dry weight) and found a significant increase in the protein content (control with 3.79% (w/w) and with 1.5% (w/w) algae 22.62% protein) and ash, but not significant in lipids. In the studies by Darwish (2017) and Golmakani et al. (2019), in addition to increasing protein, ash also increased, which was justified by the content of *S. platensis* added, another organism rich in proteins (accounting for approximately 60% protein) (Radhakrishnan et al., 2017) and approximately 10% ash (Agustinia et al., 2016). *Spirulina* sp. was investigated in two other studies. Bosnea et al. (2020) found a slight increase in protein content and fat when concentrations of 0.25%, 0.5% and 1% of *Spirulina* sp. were added, however, in other experiments, the authors found an increase in the protein for all the concentrations tested, namely 1%, 2% and 3%, although for this last content, only the lipids present in the final product decreased. Moreover, there was also an increase in carbohydrates and a decrease in ash and pH.

Table 2.

Contrary to the normal procedure, in which the authors studied the addition of the algae biomass directly on the products, Davoodi et al. (2023) and Iry et al. (2023) have changed the approach, since, instead of applying the biomass directly, these authors added *Spirulina* sp. extracts rich in phycocyanin (PC) to cheese. The use of these extracts can enhance sensory properties by masking the characteristic algae odor often perceived by consumers. Additionally, their higher concentration enhances the content and bioactivity of beneficial compounds. Davoodi et al. (2023) found an increase in protein (93% w/w), fat (80% w/w), ash (67% w/w) and a decrease in pH. Iry et al. (2023) also found an increase in protein and a decrease in pH.

3.2 Color parameters

From the studies performed using algae in the production of cheese, only 3 investigated the coloration of the final product (Table 3), by using the Hunter color parameter: (L*: brightness, a*: redness-greenness, and b*: yellowness-blueness). Mohamed et al. (2020) used *Spirulina maxima* in cheese analogue, found that there was a decrease in the L* value with the increase in the concentration of algae, meaning that more algae, the less brightness. The value of a* also decreased, showing that the cheese has a greener color, due to the chlorophyll content in the algae (Fradique et al., 2010). The b* value doubled with the highest concentration of 3%, showing a tendency towards blue. Two studies investigated the addition of *Spirulina platensis* in the production of cheeses obtaining the same results. Golmakani et al. (2019) and Darwish (2017) found a decrease in the L* value (85.67 to 56.33 and 95.80 to 74.73, respectively), and the a* value also decreased, showing more greenness, as in the study by Mohamed et al. (2020). The b* value decreases in both studies, indicating increased yellowness. These two articles also evaluated color through sensory analysis. Golmakani et al. (2019) found that with 0.5% and 1% seaweed, the color received higher scores, while Darwish (2017) found that the 1% concentration was better accepted. In both studies, a 1.5% concentration resulted in lower scores. Additionally, Darwish (2017) used small grains of *S. platensis* in the cheese, and the resulting color was well accepted, as it resembled that of Roquefort cheese.

Table 3.

3.3 Sensory analysis

Sensory analysis of food is crucial for determining consumer acceptability, product improvement, and commercialization. The main characteristics studied in the sensory analysis of cheese were firmness, which refers to the product's resistance to deformation (Mohamed et al., 2013), stickiness, defined as the tendency of the product to adhere to a contact surface (Adhikari et al., 2001), and overall acceptability by panelists (Table 4). The two studies involving *C. vulgaris* yielded similar results. The firmness of the cheese increased with higher concentrations of the algae, while stickiness decreased. Mohamed et al. (2013) found that among concentrations of 1%, 2% and 3%, the 2% concentration did not have a significant effect on the overall acceptability score. Tohamy et al. (2018) observed that at higher concentrations (2%, 4% and 6%), the cheese with 6% was rejected due to significant differences in sensory properties. The 2% concentration was the most accepted, followed by 4%. With *S. maxima*, Mohamed et al. (2020) also found an increase in cheese firmness and a decrease in stickiness. While all concentrations (1%, 2% and 3%) were accepted, the 1% concentration was preferred. Similarly, Bosnea et al. (2020) found that cheeses with 0.25% and 0.5% were better accepted than those with 1%, due to the milder odor and taste of *S. maxima* at lower concentrations.

Table 4.

Darwish (2017) found that the addition of 0.5% and 1% of *S. platensis* to Kareish cheese resulted in no significant difference in sensory qualities between the two concentrations. However, the addition of 1.5% caused a noticeable darkening of the cheese, leading to consumer rejection in the initial experiments. A similar outcome was reported by

Golmakani et al. (2019), where the 1.5% concentration of *Spirulina* was significantly less pleasant, while the samples with 0.5% or 1.0% received similar scores for odor, texture, and consistency.

3.4 Microbiology

Microbiological assessment is crucial for cheesemakers, especially because cheese can be made from raw milk, which is highly perishable. While microorganisms in cheese contribute to desirable organoleptic attributes, some can have negative effects. Various studies have explored the impact of adding algae on the microbiological properties of cheese. Faustino et al. (2023) investigated the potential prebiotic effects of cheese spreads containing *O. pinnatifida* by using pure probiotic cultures of *Lactobacillus acidophilus LA-5®* and *Bifidobacterium animalis* subsp. *lactis BB-12®*. They found that the cheese with algae exhibited prebiotic potential, with *L. acidophilus* being more effective than *B. animalis*. Additionally, no microbial contamination was detected. Yilmaz-Ersan et al. (2024) found that the viability of *L. acidophilus* in probiotic cheese with *C. vulgaris* ranged from 7.13 to 6.76 log CFU/g, while in probiotic cheese with *S. platensis*, it ranged from 7.91 to 7.28 log CFU/g after 90 days of ripening. To be considered probiotic, a food must contain at least 10^6 CFU/g of probiotic microorganisms (Gul et al., 2024), indicating that the cheeses meet the recommended ranges.

Bosnea et al. (2020) found that different concentrations of incorporated *Spirulina* sp. (0.25%, 0.5%, 1%) did not affect the final microbiological profile of the cheese. This analysis included the evaluation of mesophilic lactobacilli, mesophilic lactococci, *Staphylococci*, total coliforms, and total enterobacteria. The only change observed was an increase in the population of yeast and molds after 60 days of storage in all cheese samples. However, the typical storage time accepted for fresh cheeses is up to 30 days after production.

3.5 Texture and Syneresis

Texture plays a crucial role in the sensory appeal of food and is closely linked to consumer expectations. High values in texture parameters may result in lower consumer acceptance if the texture is deemed unsuitable for a particular type of food. These parameters are also useful for comparing a new product to a control. Table 5 presents the texture changes observed with the addition of *S. platensis* in two studies. Golmakani et al. (2019) found a decrease in hardness compared to the control, with no significant differences between the concentrations of algae incorporation (0.5%, 1.0%, and 1.5%). The cheese with higher algae content and lower hardness demonstrated greater activity of protease enzymes. There were no significant differences between the cohesiveness and adhesiveness of the samples and the control. The control and samples with 0.5% and 1.0% of *Spirulina* sp. exhibited more springiness than those containing 1.5%.

Table 5.

There were also no significant differences in gumminess and chewiness between the control and the 0.5% and 1.0% samples, although these parameters were higher in the control than in the 1.5% concentration of *S. platensis* sample. Negligible levels of syneresis were observed in all three cheese samples, indicating that the addition of algae and the reduction of acidity did not adversely affect the gel network. Darwish (2017) obtained different results for Kareish cheese, finding that there was a difference among all cheeses fortified with *S. platensis*. Hardness, cohesiveness, gumminess and chewiness increased with the concentration of algae, but springiness decreased. The increase in hardness may have been due to the increase in dry matter (Mazinani et al., 2016). In this study, the 3 concentrations (0.5%, 1.0% and 1.5%) improved the development of the texture parameters.

3.6 Bioactivities studied for the algae-based cheese

The studies examining the bioactive compounds in algae-fortified cheese are presented in Table 6. Faustino *et al.* (2023) studied three activities: antidiabetic, antihypertensive and antioxidant. To verify whether there was an antidiabetic potential, they used α-glucosidase inhibitor compounds, which can delay glucose absorption by inhibiting the activity of carbohydrate digestive enzymes, controlling the glycemic level. It was found that the cheese with the extract of macroalga *O. pinnatifida* obtained 8.95% inhibition of α-glucosidase after 21 days of refrigerated storage, whereas no α-glucosidase inhibition was detected in the control cheese. In another study, higher levels of α-glucosidase inhibition were reported for *O. pinnatifida*. However, similar levels were not achieved in this study, due to the thermal treatment applied during processing. *Osmundea pinnatifida* was also demonstrated to have a good antihypertensive activity, presenting an activity of 68% in the algal extract and between 50-57% in the cheese enriched with the alga. The antioxidant activity in the cheese with the alga was increased, demonstrated through the methods ABTS, DPPH, and hydroxyl radicals (Faustino et al. 2023). With *S. maxima*, Mohamed et al. (2020) found that as the concentration of algae increased, the antioxidant activity (measured by DPPH free radical) also increased, from 5.52% for the control to 57.24% for the cheese with 3% of algae. Similarly, with *S. platensis*, Darwish (2017) observed an increase in the antioxidant activity, though it was less pronounced than what Mohamed et al. (2020) reported, around 4.2% in the control and 4.7% in cheese enriched with 1.5% of algae.

Table 6.

The increase in chlorophyll content may have contributed to the free radical scavenging activity (Lopez *et al.,* 2011). Darwish (2017) also noted an increase in phenolic compounds (14.52 mg gallic acid equivalents (GAE)/100 g in the control and 18.44 mg GAE/100 g with 1.5% of seaweed added) and β-carotene (0.191 mg/100 g in the control and 1.020 mg/100 g with 1% of seaweed), although the overall values remained low. In another study using *S. platensis*, Agustini *et al.* (2016) reported a more substantial increase in β-carotene, from 0.57 mg/100 g in the control to 8.08 mg/100 g with 1.5% of seaweed added.

4. Yogurt

Nineteen articles were found that investigated the incorporation of algae into yogurt (Table 7). The most used microalgae were *S. platensis* and *C. vulgaris*, similar to what was observed in the cheese production studies. However, other microalgae such as *Aurantiochytrium sp.*, *Pavlova lutheri*, *Isochrysis galbana,* and *Dunaliella salina* were also investigated, along with the only macroalga, *Undaria pinnatifida*. Three studies focused on extracting lipids from algae (referred to as algae oil) to enrich yogurt with omega-3 fatty acids, assessing oxidative deterioration and stability. Additionally, three studies extracted phycobiliproteins (e.g. phycocyanin) and the carotenoid fucoxanthin from algae for yogurt production. The concentrations of algae incorporated ranged from 0.25% to 2%, with up to 8% for extracted phycobiliproteins and up to 10% for fresh algae. Researchers also evaluated whether the algae were added before or after yogurt fermentation, as this timing could impact the results. The studied characteristics of yogurt will be detailed in the following sections.

Table 7.

4.1 Physicochemical composition

The most commonly analyzed components in yogurt were protein, fat, carbohydrates, ash, moisture, and pH, with values categorized by algae species (Table 8). pH values were specifically highlighted in Table 8, as they are particularly important in studies involving algae incorporation into yogurt. Most studies reported an increase in protein content when yogurt was fortified with *S. platensis*. For example, Barkallah et al. (2017) found that even a small addition of 0.25% of *S. platensis* significantly increased the protein content compared to the control, while Dinçoğlu et al. (2024) and Arslan & Aksay (2022) observed similar increases with 1% and 1.5% additions, respectively. In another study, yogurt fortified with 2% of *I. galbana* showed an increase in protein content (Matos et al., 2021). Pan-utai et al. (2020) tested both oven-dried (0.1%, 0.3%, and 5%) and fresh (1%, 5%, and 10%) *S. platensis*, but found that all components remained similar to those in the control, despite the algae's high protein content. A similar outcome was reported by Robertson et al. (2016) when incorporating *Pavlova lutheri* lipid extract, as none of the yogurt components were significantly altered by the addition of the extract at 0.25% or 0.5%. Dinçoğlu et al. (2024) found no significant difference in lipid content when adding algae to yogurt, but there was a significant increase in ash content. Similarly, using *S. platensis*, Barkallah et al. (2017) observed a slight increase in lipid levels, as well as in all other components. Arslan and Aksay (2022) found that as the concentration of seaweed increased, the lipid content decreased significantly compared to the control, although the decrease in carbohydrate content was not statistically significant. At a concentration of 1.5%, they also observed an increase in ash content. With *I. galbana*, there was no significant increase in lipid content, but a decrease in yogurt moisture and an increase in ash were noted (Matos et al., 2021).

Table 8.

The pH was measured at the start and end of fermentation, as well as throughout storage (Table 9). Both Beheshtipour et al. (2012) and Barkallah et al. (2017) reported no significant difference in pH levels at the end of fermentation between different concentrations of *S. platensis*. However, the decline in pH was higher with the algae addition compared to the control. Beheshtipour et al. (2012) also found that *S. platensis* led to a higher acidification rate than *C. vulgaris*. Pan-utai et al. (2020) reported a similar decrease in pH at the end of fermentation for both oven-dried and fresh *S. platensis* compared to the control. It was found out that during 28 days of storage, *S. platensis* exhibited minimal pH changes. This increased acidity is considered an advantage, because the addition of algae to yogurt supports the growth of lactic acid bacteria. Nourmohammadi et al. (2020) observed a significant decrease in pH over 15 days due to bacterial activity. Kazemeini et al. (2023)

found no significant difference up to 21 days of storage, but a change was noted after 35 days. They also increased the algae concentration to 2%, resulting in a lower pH due to the buffering capacity in samples containing microalgae. Dinçoğlu et al. (2024) noted that the decrease in pH over 28 days was more controlled with algae, demonstrating a higher buffering capacity. Mohammadi-Gouraji et al. (2018) and Sangian et al. (2022), who used phycocyanin extracted from *S. platensis*, observed stable pH levels over 15 and 21 days of storage, respectively, even at a concentration of 8% of phycocyanin.

Table 9.

4.2 Color parameters

Given the significant impact of color on consumer acceptance of dairy products, the color of yogurt was assessed at various algae concentrations, including at the end of storage (Table 10). Barkallah et al. (2017), Nourmohammadi et al. (2020), and Arslan & Aksay (2022) found that adding *S. platensis* to yogurt decreased the L*, a*, and b* values, making the yogurt less bright, greener, and bluer. Pan-utai et al. (2020) reported that yogurt with fresh *S. platensis* exhibited increased whiteness and blueness compared to yogurt with oven-dried algae, which in turn appeared greener. When yogurt was supplemented with phycocyanin extracted from *S. platensis*, both a* and b* values increased, corresponding to higher brightness with increasing protein concentrations (2%, 4%, and 8%), consistent with the blue hue of this phycobiliprotein. The color remained stable over 21 days of storage. A similar trend was observed in the study by Sangian et al. (2022), though the effect was more subtle due to the lower concentrations used (0.5%, 1.0%, and 1.5%). The color of yogurt was also evaluated with the addition of fucoxanthin from *Undaria pinnatifida*, another pigment present in algae, which belongs to the family of carotenoids. While there was no significant change in the overall brightness of the yogurt, there was an increase in a* and b* values on the first day, resulting in a redder and yellower appearance. During storage, the brightness has decreased while the red and yellow colors were intensified, probably due to the inherent color of fucoxanthin. The color of yogurt containing lipid extract from *Pavlova lutheri* remained unchanged over 28 days of storage. However, a significant decrease in brightness was observed between the control and the yogurt with added algae concentrations (0.25% and 0.5%), along with an increase in greenness and yellowness.

Table 10.

4.3 Sensory Analysis

In yogurt, the most assessed characteristics in sensory analysis were color, texture, flavor, and overall acceptability (Table 11). In studies involving *S. platensis*, scores for color, texture, and acceptability generally decreased with increasing algae concentration. Akalin et al. (2009) and Arslan and Aksay (2022) found that a concentration of 0.5% was most acceptable for the color parameter, while Barkallah et al. (2017) reported that 0.25% algae was preferred. Beheshtipour et al. (2012) found no significant difference in color and texture between concentrations of algae of 0.25% and 0.5%, although they did observe differences in flavor. Barkallah et al. (2017) noted significant differences in texture, flavor, and acceptability, particularly at concentrations exceeding 0.25% of seaweed. Nourmohammadi et al. (2020) were unique in testing a higher concentration of 2%, which also resulted in decreased scores for color and texture. Dinçoğlu et al. (2024) reported no differences in color in their yogurt samples. The flavor rejection by evaluators may be attributed to lipid and mineral oxidation in *S. platensis*, which can produce a metallic taste (Shimamatsu, 2004). For *C. vulgaris*, Beheshtipour et al. (2012) found no significant differences between 0.25% and 0.5% concentrations, but the sensory scores were higher compared to *S. platensis*. The addition of algae oil can introduce a fishy flavor to products, making sensory analysis essential. In a study by Chee et al. (2005), a trained panel detected this flavor, but it did not adversely affect the overall acceptability of the product. He et al. (2023) found that encapsulated algae oil had better acceptability in yogurt compared to raw algae oil. In contrast, algae oil from *Pavlova lutheri* was not accepted in terms of flavor, color, or overall acceptance. Sangian et al. (2022) found that adding phycocyanin up to 1.5% resulted in slightly lower texture and flavor scores compared to the control. However, in the study by Mohammadi-Gouraji et al. (2018), yogurt with 8% of phycocyanin was considered acceptable regarding color, but it received more favorable feedback from panelists at concentrations of up to 4%. The color of yogurt containing fucoxanthin was highly rated and well accepted by panelists (Wang et al., 2023).

Table 11.

4.4 Microbiology

The viability of probiotic microorganisms in a product until the time of consumption is a critical quality parameter. While there is no global consensus on the minimum number of viable probiotic cells required, a count of 10^6 CFU/mL or CFU/g *per* day is generally accepted as the minimum to achieve health-promoting effects (Vivek et al., 2023). Akalın et al. (2009) added *S. platensis* to yogurt after fermentation and monitored the cell viability over 30 days of storage. The yogurt containing algae had higher levels of lactic acid bacteria than the control, with counts remaining above 10^6 CFU/g by the end of the storage period. Similarly, Dinçoğlu et al. (2024) observed increased levels of *L. acidophilus* and *B. animalis* with the addition of algae during 28 days of storage. Beheshtipour et al. (2012) reported increased viability of *L. acidophilus* and bifidobacteria both at the end of fermentation and throughout storage, with counts reaching nearly 10^7 CFU/mL for yogurts containing *S. platensis* and *C. vulgaris*. Additionally, the growth index for yogurts with microalgae was significantly higher than that of the control, particularly for *L. acidophilus*. Khaledabad et al. (2019) found that with 0.5% of algae supplementation, probiotic populations remained above 10^8 CFU/g throughout the storage period. Similarly, Kazemeini et al. (2023) observed a significant increase in probiotic viability, maintaining counts above 10^7 CFU/mL until the end of storage. The addition of up to 8% of phycocyanin to yogurt had no significant impact—positive or negative—on *S. thermophilus* compared to the control and after 21 days of storage (Mohammadi-Gouraji et al., 2018). Sangian et al. (2022) found a slight increase in lactic acid bacteria with phycocyanin concentrations up to 1.5% on the first and 15th days of storage compared to the control, with levels remaining stable throughout the storage period. In conclusion, adding algae to yogurt supports a favorable environment for lactic acid bacteria during both fermentation and storage. Compounds found in algae, such as amino acids, vitamins, and γ-linolenic acid, can enhance the proliferation of proteolytic probiotics, while polysaccharides in algae are already recognized as prebiotics (Khaledabad et al., 2019; Niccolai et al., 2019).

4.5 Texture and Syneresis

The most commonly studied texture parameters in yogurt are firmness, cohesiveness, consistency, and viscosity. Susceptibility to syneresis (STS), an undesirable trait in yogurt, refers to the spontaneous rearrangement of the gel network, leading to whey separation. Water holding capacity (WHC), which measures the ability to retain water under external forces, depends mainly on the microstructure of the protein network in yogurt. A comparison of these parameters is provided in Table 12. In the study by Barkallah et al. (2017), increased concentrations of *S. platensis* have reduced the firmness of the yogurt by disrupting its gel network. However, there was no difference in cohesiveness compared to the control. Whey release (STS) was higher, and WHC was lower in the control yogurt than in the yogurt with added algae, likely due to the high protein, fat, and fiber content of the microalgae. During a 15-day storage period, Nourmohammadi et al. (2020) found that both control and fortified yogurts experienced a decrease in WHC and an increase in STS, attributed to lactic acid production, which can weaken the protein network. In the study by Pan-utai et al. (2020), yogurt with fresh *S. platensis* showed higher WHC than those with oven-dried algae. Throughout a 28-day storage period, WHC increased across all concentrations (0.5%, 0.75%, and 1.5%) as well as among them (Dinçoğlu et al., 2024). In the same study, hardness values were higher in the control and yogurt with 0.5% of *S. platensis* compared to those with 0.75% and 1%. Additionally, resilience was lower in the control, while elasticity was greater in the fortified yogurts. Phycocyanin-fortified yogurt (2%, 4%, and 8%) exhibited lower syneresis compared to the control, and during storage, STS decreased across all treatments (Mohammadi-Gouraji et al., 2018). The increased total solid content helped stabilize the gel network, leading to improved WHC. Sangian et al. (2022) found no significant difference in WHC and STS, possibly due to the lower concentration of phycocyanin used, up to 1.5%. However, the control group had the highest hardness and springiness, while viscosity increased with higher concentrations of phycocyanin. Yogurt fortified with fucoxanthin exhibited lower values for hardness, consistency, and viscosity, suggesting that this pigment alters the gel structure of yogurt (Wang et al., 2023). Although no significant difference in syneresis was observed with the addition of algae oil from *Pavlova lutheri*, it may help reduce the syneresis rate after 28 days of storage (Robertson et al., 2016).

Table 12.

4.6 Bioactivities studied for the algae-based yogurt

Only four articles examined the antioxidant activity in algae-fortified yogurts (Table 13). *Spirulina*'s antioxidant effects are reported to prevent or slow the adverse impacts of free radicals (Ismaiel et al., 2016). Barkallah et al. (2017) assessed antioxidant activity using DPPH and FRAP methods and found that yogurts fortified with *S. platensis* had higher antioxidant levels than the control. With an alga concentration of 0.25%, the authors observed 52.41% of DPPH radical scavenging activity. Another study showed that adding 1% of *S. platensis* yielded 77% of DPPH radical scavenging activity, which decreased to 56% after

28 days of storage (Dinçoğlu et al., 2005). Similarly, Khaledabad et al. (2019) noted a reduction in antioxidant activity over the storage period. This decline, observed in both studies, may be attributed to the proteolytic activity of *L. paracasei*, which degrades C-phycocyanin (Donkor et al., 2007). Wang et al. (2023) reported increased antioxidant activity with the addition of fucoxanthin from *Undaria pinnatifida* compared to the control, with even better results when the fucoxanthin was encapsulated.

Table 13.

5. Challenges and areas for future research

From the analysis of studies on yogurt and cheese fortified with algae, it is evident that incorporating algae into dairy products offers both advantages and challenges. Algae and cyanobacteria, such as *S. platensis* and *C. vulgaris*, can enhance the nutritional content of yogurt and cheese, since they increase the protein levels and contribute beneficial compounds like antioxidants, essential amino acids, and vitamins when incorporated in these dairy products. Algae also play a relevant role in supporting the growth and viability of probiotic bacteria, which is essential for the health benefits of these products. The use of algae has been shown to have an impact on the texture and sensory properties of dairy products, with some studies noting changes in firmness, cohesiveness, and water-holding capacity. While fortified products may have a different texture compared to the control, they can maintain desirable qualities, such as higher water retention in yogurt, which can help prevent syneresis. However, sensory properties like flavor and color may become less appealing at higher algae concentrations, often leading to a decrease in consumer acceptability. Finally, it seems from the results analyzed in this work that algae can create a more favorable environment for lactic acid bacteria during storage, maintaining high probiotic viability. They also contribute to a faster acidification rate, which can be beneficial for yogurt fermentation. Yet, the decrease in pH and alterations in taste due to algae can be a concern for long-term storage and flavor preferences. Summing up, algae have the potential to improve the nutritional profile of yogurt and cheese, offering enhanced probiotic support and a range of bioactive compounds. However, balancing the sensory aspects like taste and texture is crucial for consumer acceptance. Further research into optimizing algae concentration and formulation can help address these challenges and increase the appeal of algae-enriched dairy products.

It is true that the demand for novel foods and ingredients derived from algae, including microalgae and seaweed, has grown significantly due to their nutritional, sensory, and technological benefits, and their alignment with sustainable food systems. Research into algae-based foods has focused on two main areas: understanding the chemical flavor compounds influencing the taste and sensory appeal and identifying the factors that drive or discourage consumers from incorporating algae into their diets. Consumer concerns are often centered on health benefits and the willingness to accept the unique taste of algae. The incorporation of algae into dairy products, like yogurt and cheese, presents promising opportunities for innovation and growth. However, achieving widespread consumer acceptance and maximizing the benefits of these products will require targeted research and key development, which are summarized in Figure 3.

Figure 3.

Firstly, a better balance between algae concentration and sensory appeal is crucial. While algae are rich in nutrients like proteins, vitamins, antioxidants, and essential fatty acids, their strong flavors can hinder consumer acceptance, especially at higher concentrations. Future research should focus on finding the optimal balance between algae level of incorporation and sensory properties (taste, texture, and appearance) to create products that are both nutritious and palatable. Since the flavor imparted by algae may not appeal to everyone, it is important to develop strategies to address this challenge. Advanced techniques like microencapsulation could help mask the distinctive taste and odor of algae, making their integration into dairy products more seamless. Another approach is using extracts and bioactive compounds that retain nutritional value without the characteristic algae flavor. In the studies analyzed, only a few extracts, such as phycocyanin, fucoxanthin, and omega-3-rich oils, were tested, but many more could be explored. This could not only enhance the nutritional profile of the products but also add new functions, such as using other pigments to provide natural coloring, thus reducing the need for synthetic additives. Additionally, this could help develop niche products with specific health claims, appealing to consumers seeking functional foods.

Future research could also explore the potential of algae in modifying the fermentation process itself. For example, certain algal polysaccharides could be studied as prebiotics, enhancing the growth of probiotics during fermentation and creating new textures in yogurt and cheese. Despite the nutritional benefits of algae, many consumers are still unfamiliar with their use in food products. Effective marketing strategies and educational campaigns that emphasize the health benefits, sustainability, and innovative nature of algae-enriched dairy products can help overcome initial hesitations. Transparency regarding sourcing and processing methods can further build consumer trust. Indeed, algae-enriched dairy products can be positioned as premium products for health-conscious consumers, especially those seeking plant-based and functional foods. The growing interest in alternative proteins and superfoods presents a promising market for such innovations. While much of the research has focused on yogurt and cheese, algae could be applied to a broader range of dairy and dairy-alternative products. Future studies could investigate algae integration in products like kefir, dairy-based smoothies, and plant-based milk alternatives, creating a diverse portfolio of functional dairy offerings.

Combining dairy with plant-based ingredients is a rising trend, and hybrid products incorporating algae could attract both traditional dairy consumers and those exploring plant-based alternatives. This approach could lead to innovations like algal-infused dairy-free cheeses or probiotic-rich beverages. Given algae's potential to promote probiotic growth, future research could focus on how different probiotic strains interact with various algal species and extracts. This could result in custom probiotic blends that work synergistically with algae to enhance gut health.

Beyond their nutritional benefits, algae contain compounds with potential antimicrobial and antioxidant properties, which could naturally extend the shelf life of dairy products. Research could explore how these properties might reduce the need for artificial preservatives, making products more appealing to consumers seeking clean-label options. Understanding how algae interact with protein and fat structures in yogurt and cheese can lead to more stable products, reducing issues like syneresis and ensuring consistent quality over time.

6. Conclusions

In conclusion, the future of algae-enriched yogurt and cheese lies in combining technological advancements with a deeper understanding of consumer preferences. By refining product formulations, exploring new applications, and highlighting the environmental and health benefits, these innovations can become more accessible and appealing to a broader audience. With ongoing research and development, algae-enhanced dairy products could play a significant role in advancing the functional food market and promoting sustainable, nutrient-rich diets.

Declarations

Ethics declarations

Conflict of interest

The authors declare no competing interests.

Ethical Approval

Nothing to declare.

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Data availability

Not applicable.

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List of Figures

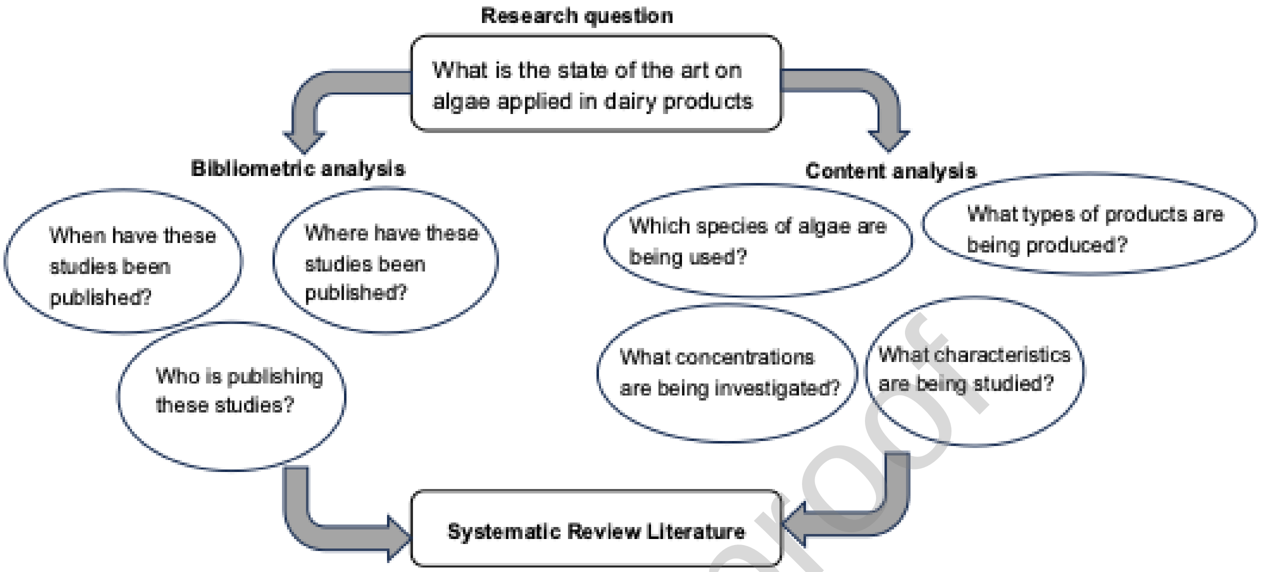

Figure 1. Diagram representing the research questions approached in this work.

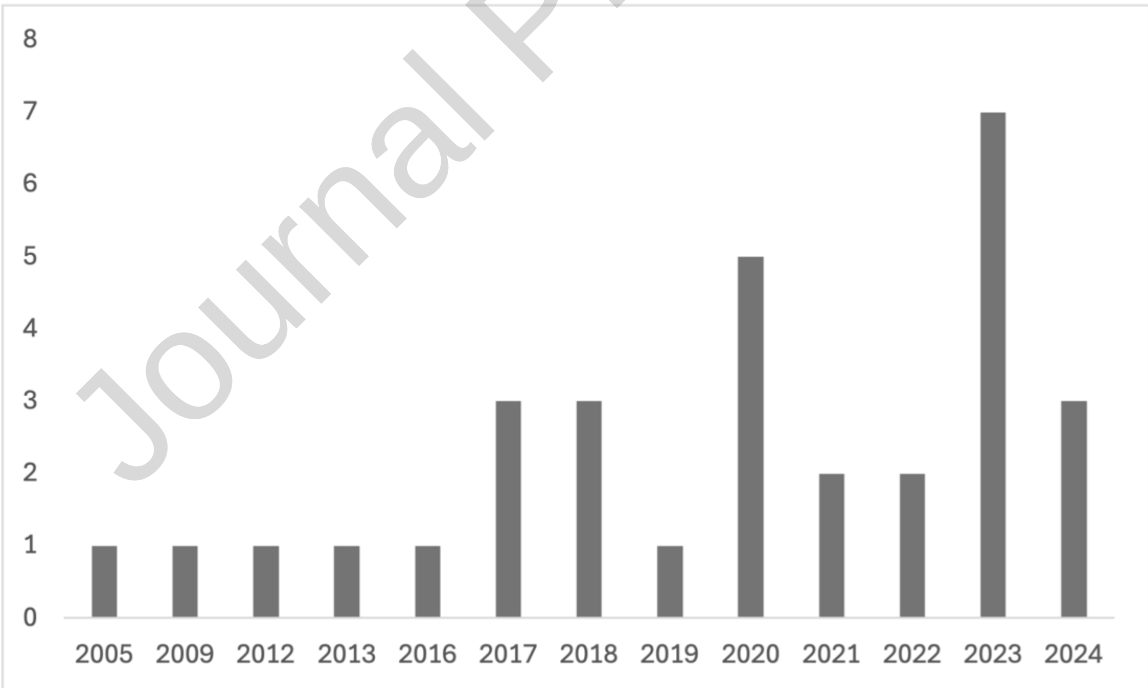

Figure 2. Number of papers published by year of publication.

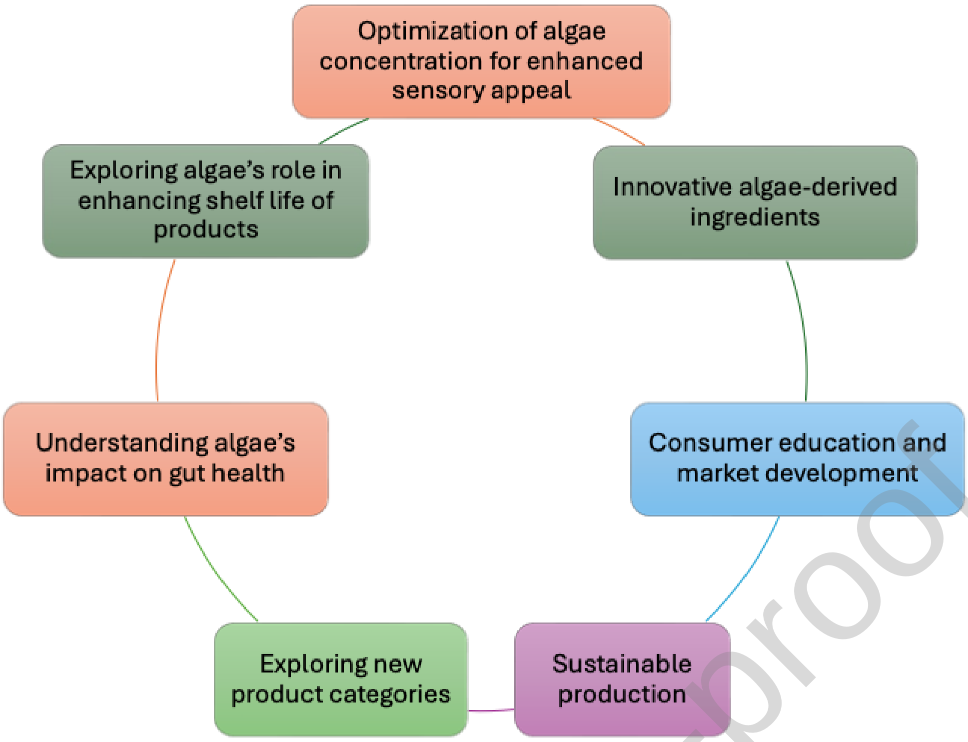

Figure 3. Main targeted research and key developments required in the field of dairy products.

Table 1. Studies on the application of algae in cheese.

Species	Type	Concentration	Applied form	Characteristics studied	References
Osmundea pinnatifida	Cheese Spread	3% (w/w)	Lyophilized-WF	Physicochemical, microbiological, antihypertensive, and antioxidant activities	Faustino et al. (2023)
Chlorella vulgaris and Spirulina platensis	Brined cheese	1 % (w/v)	Lyophilized-WF	Microbiological, Physicochemical and metabolomic characterization	Yilmaz-Ersan et al. (2024)
Chlorella vulgaris	Cheese analogue	1%, 2% and 3% (w/w)	Lyophilized-WF	Physicochemical and sensory properties	Mohamed et al. (2013)
	Cheese analogue	Dried 2%, 4% and 6% (w/w); Slurry 4% (w/w)	Lyophilized and slurry-WF	Physicochemical and sensory properties	Tohamy et al. (2018)
Phycocyanin from Spirulina sp.	Iranian cheese	1%, 1.5% and 2% (w/w)	AF	Physicochemical, sensory and antioxidant properties	Davoodi et al. (2023)

	Traditional cheeses	1%	-	Physicochemical, microbiological and antioxidant properties. Identification of volatile compounds	Iry et al. (2023)
Spirulina platensis	Soft cheese	0.5%, 1%, 1.5% (w/w)	Lyophilized-AF	Physicochemical	Agustini et al. (2016)
	Feta-type cheese	0.5%, 1.0% and 1.5% (w/v)	Lyophilized-AF	Chemical, texture, color, syneresis and sensorial properties	Golmakani et al. (2019)
	Kareish cheese	0.5%, 1% and 1.5% (w/v)	Lyophilized-AF	Physicochemical, organoleptic properties, phenolic compounds, flavonoids, β-carotene, antioxidant capacity, color and texture properties	Darwish (2017)
Spirulina maxima	Fresh soft cheese	0.25%, 0.5%, and 1% (w/w)	Lyophilized-AF	Physicochemical, Microbiological, and Sensory properties	Bosnea et al. (2020)
	Cheese analogue	1%, 2% and 3% (w/w)	Lyophilized-WF	Physicochemical, color, sensorial, and antioxidant properties	Mohamed et al. (2020)

WF- Without Fermentation; AF- After Fermentation

Table 2. Physicochemical composition of cheese fortified with algae.

Species	Protein (%)	Fat (%)	Carbohydrates (%)	Ash (%)	pH	References
Osmundea pinnatifida	C: - 3%: 5.05	C: - 3%: 7.87	-	-	C: 5.95 3%: 5.61	Faustino et al. (2023)
Chlorella vulgaris	C: 11.86 1%: 13.23	C: 12.71 1%: 11.29	-	-	-	Yilmaz-Ersan et al. (2024)
	C: 13.56 1%: 14.38 2%: 14.49 3%: 14.70	C: 50.16 1%: 49.72 2%: 48.53 3%: 47.92	C: 2.90 1%: 3.95 2%: 3.91 3%: 4.85	C: 4.36 1%: 3.60 2%: 3.74 3%: 3.76	C: 5.80 1%: 5.42 2%: 5.40 3%: 5.39	Mohamed et al. (2013)
	C:12 2%: 12.13 4%: 12.25	C 19.5 2%: 19.8 4%: 20.5	-	C: 2.26 2%: 2.93 4%: 3.05	C: 5.77 2%: 5.92 4%: 6	Tohamy et al. (2018)
	C: 11.86 1%: 13.40	C: 12.71 1%: 9.44	-	-	-	Yilmaz-Ersan et al. (2024)
	C: 3.79 1%: 16.44 1.5%: 22.62	C: 3.16 1%: 3.31 1.5%: 3.46		C: 2.37 1%: 2.55 1.5%: 2.46		Agustini et al. (2016)
	C: 12.24 0.5%: 12.82 1%: 12.93 1.5%: 13.15	C:3.13 0.5%:3.28 1%: 3.34 1.5%:3.36	-	-	-	Golmakani et al. (2019)

Spirulina platensis	C: 13.34±0.05 0.5%: 13.44±0.07 1%: 12.11±0.04 1.5%: 14.6±0.1	C: 0.24±0.01 05%: 0.28±0.01 1%: 0.28±0.03 1.5%:0.3	-	C: 2.41±0.05 0.5%: 2.42±0.09 1%: 2.8±0.1 1.5%: 3.0±0.1	-	Darwish (2017)
	C: 11.0±0.2 0.25%: 11.2±0.4 0.5%: 11.55 1%: 12.1±0.3	C: 11.5±0.0 0.25%: 11.7±0.3 0.5%: 12.0±0.3 1%: 12.5±0.3	-	-	-	Bosnea et al. (2020)
Spirulina maxima	C: 13.66 1%: 14.38 2%: 14.46 3%: 14.67	C: 50.00 1%: 50.01 2%: 49.88 3%: 49.71	C: 2.90 1%: 3.90 2%: 3.95 3%: 4.75	C: 4.96 1%: 3.65 2%: 3.80 3%: 3.83	C: 5.81 1%: 5.65 2%: 5.63 3%: 5.62	Mohamed et al. (2020)

The percentages shown in the table refer to the concentration of algae biomass added to the cheese. C: Control.

Table 3. Color parameters determined for cheese fortified with algae.

Species	L	a	b	References
Spirulina maxima	C: 87.13 1%: 82.11 2%: 79.15 3%: 74.11	C: -1.30 1%: - 6.51 2%: -7.95 3%: -10.50	C: 17.88 1%: 23.66 2%: 30.90 3%: 34.65	Mohamed et al. (2020)
Spirulina platensis	C: 85.67 ± 3.06 0.5%: 64.33 ± 2.08 1.0%: 60.33± 1.53 1.5%: 56.33 ± 3.06	C: 5.67 ± 0.58 0.5%: -7.33 ±1.15 1.0%: -11.67± 0.58 1.5%: -10. ± 0.58	C: 11.33± 0.58 0.5%: 8.00±1.00 1.0%: 5.33 ±1.15 1.5%: 3.67±1.15	Golmakani et al. (2019)
	C: 95.80 ±0.02 0.5%: 80.46 ±0.01 1.0%: 76.26 ±0.01 1.5%: 74.73 ±0.01	C: - 1.02±0.01 0.5%: -6.89±0.03 1.0%: -9.88±0.02 1.5%: -10.69±0.01	C: 7.33±0.02 0.5%: 7.79±0.02 1.0%: 7.71±0.01 1.5%: 5.78±0.01	Darwish (2017)

The percentages shown in the table refer to the concentration of algae biomass added to the cheese. C: Control.

Table 4. Effect on sensory properties of cheese fortified with algae.

Species	Scale	Firmness	Stickiness	Acceptability	References
Chlorella vulgaris	Firmness: 1-7 Stickiness: 1-5 Acceptability: 1-7	C: 6.80 1%: 6.82 2%: 6.90 3%: 6.90	C: 5.00 1%: 4.91 2%: 4.95 3%: 4.86	C: 7.00 1%: 6.8 2%:6.95 3%:6.77	Mohamed et al. (2013)
	Firmness: (1) very soft-(5) very firm Stickiness: 1) not sticky-(5) very sticky Acceptability: (1) dislike very much -(5) like very much	C: 2 2%: 2 4%: 2.5 6%: 3	C: 3 2%: 2 4%: 2 6%: 1	C: 4,5 2%: 4 4%: 3 6%: 2	Tohamy et al. (2018)
	Firmness: (1) very firm-(7) very soft Stickiness: (1: Very sticky, 7: Not sticky) Acceptability: 1: Very poor acceptability, 7: Very good acceptability)	C:6,88 1%:6,96 2%: 6.90 3%: 6.85	C: 6,58 1%: 6.57 2%: 6.60 3%: 6.65	C:7,00 1:6.97 2%:6.95 3%:6.86	Mohamed et al. (2020)
	Firmness: 35 Acceptability: 100	C: 33.0±0.7 0.5%: 32.5±0.4 1.0%: 33.0±0.4 1.5%: 33.5±0.5	-	C: 95.5±2.1 0.5%: 82.0±0.9 1.0%: 91±1 1.5%: 79.0±0.7	Darwish (2017)

The percentages shown in the table refer to the concentration of algae biomass added to the cheese. C: Control, WN: Without Number.

Table 5. Texture and syneresis data for cheese fortified with algae.

Species	Texture						Syneresis (%)	References
	Hardness	Cohesiveness	Chewiness	Gumminess	Springiness	Adhesiveness		
Spirulina platensis	C: 71.75 ± 6.72 0.5%: 63.50 ± 7.07 1.0%: 54.75 ± 2.47 1.5%: 58.75 ± 4.60	C: 0.46 ± 0.12 0.5%: 0.48 ± 0.04 1.0%: 0.44 ± 0.09 1.5%: 0.45 ± 0.15	C: 1.43 ± 0.30 0.5%: 1.20 ± 0.04 1.0%: 1.18 ± 0.16 1.5%: 1.00 ± 0.45	C: 32.40 ± 5.37 0.5%: 26.05 ± 3.04 1.0%: 27.30 ± 2.69 1.5%: 26.45 ± 10.82	C: 4.48 ± 0.21 0.5%: 4.28 ± 0.20 1.0%: 4.39 ± 0.18 1.5%: 3.81 ± 0.21	C: 0.24 ±0.08 0.5%: 0.29 ± 0.15 1.0%: 0.40 ± 0.04 1.5%: 0.27 ± 0.12	C: - 0.5%: 0.025 1.0%: 0.125 1.5%: 0.290	Golmakani et al. (2019)

	C: 4.4 ± 0.6 0.5%: 4.5± 0.5 1.0%: 4.7± 0.7 1.5%: 4.9± 0.5	C:0.28±0.02 0.5%: 0.33 ± 0.04 1.0%: 0.27 ± 0.02 1.5%: 0.33 ± 0.01	C:0.49 ± 0.25 0.5%: 0.68 ± 0.08 1.0%: 0.59 ± 0.12 1.5%:0.71 ± 0.10	C: 1.21 ± 1.22 0.5%: 1.47± 0.41 1.0%: 1.29 ± 0.53 1.5%:1.61 ± 0.64	C:0.404 ± 0.07 0.5%: 0.46 ± 0.05 1.0%: 0.46 ± 0.03 1.5%:0.44 ± 0.02	-	-	Darwish (2017)

The percentages shown in the table refer to the concentration of algae biomass added to the cheese. C: Control.

Table 6. Bioactive compounds/effects of cheese fortified with algae.

Species	**Antidiabetic (%)**	**Antihypertensive (%)**	**Antioxidant Activities**			**Total Phenols (mg GAE/100 g)**	**β-carotene (mg/100 g)**	**References**
			ABTS (%)	**DPPH (%)**	**Hydroxyl Radical (%)**			
Osmundea pinnatifida	8.95 ± 0.70	Extract: 68.04 ± 3.70 CS: 57.40 ± 1.52	C: 10.15 ± 0.64 CS: 14.34 ± 0.94	C: 2.78 ± 0.41 CS: 4.47 ± 0.53	C: 68.07 ± 0.60 CS: 74.71 ± 0.75			Faustino et al. (2023)
Spirulina platensis							C: 0.57 ± 0.12 1.0%: 4.25 ± 0.77 1.5%: 8.08 ± 0.84	Agustini et al. (2016)

	C: 4.199 ±0.13 0.5%: 4.39 ±0.22 1.0%: 4.22 ±0.09 1.5%: 4.69 ±0.15	C: 14.52±0.23 0.5%: 17.95±0.36 1.0%: 17.26±0.33 1.5%: 18.44±0.27	C: 0.19±0.07 0.5%: 0.55±0.15 1.0%: 0.61±0.10 1.5%: 1.02±0.04	Darwish (2017)
Spirulina maxima	C: 5.52 1%: 33.68 2%: 42.54 3%: 57.24			Mohamed et al. (2020)

The percentages shown in the table refer to the concentration of algae biomass added to the cheese. C: Control; CS: Cheese spread

Table 7. Studies on the application of micro and macroalgae in yogurt.

Species	Concentration	Applied form	Characteristics studied	References
Algae oil (Omega-3)	500 mg v-3 PUFA per 272g of yogurt white mass- BF	Emulsion	Chemical and sensory analysis	Chee et al. (2005)
Algae oil from *Chlorella vulgaris*	35.4% omega-3 fatty acids - BF	Lyophilized	Emulsion stability, texture and sensory properties	He et al. (2023)
Lipid extract *Pavlova lutheri*	0.25% and 0.5% (w/v) - BF	Liquid extract	Techno-functional properties, fatty acid analysis and sensory properties	Robertson et al. (2016)
Spirulina platensis	0.5% and 1.0% (w/w) - AF	Lyophilized	Microbiological analysis	Akalın et al. (2009)

	0.25%, 0.5%, 0.75% and 1%- BF	Lyophilized	Physicochemical, textural, color, antioxidant and sensory properties	Barkallah et al. (2017)
	2% (w/v) -BF	Lyophilized	Physicochemical properties and sensorial	Nourmohammadi et al. (2020)
	Oven-dried: 0.1%, 0.3%, and 0.5% (w/v)- BF Fresh: 1%, 5%, and 10% (v/v) - BF	Oven-dried and fresh	Physicochemical and color	Pan-utai et al. (2020)
	-	-	Physicochemical, microbiological and sensory properties	Yağmur et al. (2023)-NF
	0.5%, 1%, and 2% - AF	Lyophilized	Microbiological and sensory properties	Kazemeini et al. (2023)
	0%, 0.5%, 0.75%, and 1% -BF	Lyophilized	Microbiological, physicochemical, textural sensory properties, and antioxidant profile	Dinçoğlu et al. (2024)
	0.5%, 1.0%, and 1.5% (w/v) - BF	Lyophilized	Physicochemical, sensorial and color properties	Arslan and Aksay (2022)
	between 0-0.5% - BF		Microbiological, antioxidative capacity, sensory and color properties	Khaledabad et al. (2019)
Spirulina platensis and Chlorella vulgaris	0.25%, 0.50%, and 1. 00% - BF	Lyophilized	Microbiological, chemical and Sensory analysis	Beheshtipour et al. (2012)
Phycocyanin from *Spirulina platensis*	2%, 4%, and 8% (w/w) - AF	Lyophilized	Microbiological, physicochemical, color, sensory properties	Mohammadi-Gouraji et al. (2018)
Phycocyanin from *Spirulina platensis*	0.5%-1.0%-1.5% (w/w) - BF	-	Physicochemical, microbiological and sensory properties	Sangian et al. (2022)
Aurantiochytrium sp	2% (w/w)	-	Characterizing the lipid fraction and determining the fatty acid bioaccessibility	Paulo et al. (2020)- NF
Dunaliella salina	0%, 0.5%, 1% and 2% (w/w)- BF	Lyophilized	Physicochemical, color, texture and sensory properties	Salehi et al. (2021)-NF
Isochrysis galbana	2% (w/w) freeze-dried and ethyl-AF	Lyophilized and lipidic extract	Physicochemical and fatty acid profile	Matos et al. (2021)
Fucoxanthin from *Undaria pinnatifida*	BF	Lyophilized	Physicochemical, texture analysis, sensory properties and simulated digestion analysis	Wang et al. (2023)

NF: Not found; BF- Before Fermentation; AF- After Fermentation.

Table 8. Physicochemical composition of yogurt fortified with algae.

Species	Protein (%)	Fat (%)	Carbohydrates (%)	Moisture (%)	Ash (%)	Reference
Spirulina platensis	C: 3.63 ± 0.03 0.25%: 3.87 ± 0.07	C: 3.38 ± 0.77 0.25%: 3.4 ± 0.68	C: 14.49 ± 0.02 0.25%: 14.66 ± 0.03	C: 77.52 ± 0.03 0.25%: 77.38 ± 0.06 [a]	C: 14.49 ± 0.02 0.25%: 14.66 ± 0.03	Barkallah *et al.* (2017)

	Oven-dried	Fresh	Oven-dried	Fresh	Oven-dried	Fresh	Oven-dried	Fresh	Oven-dried	Fresh	
	C: 18.43 ± 0.04 0.1%: 17.89 ± 0.57 0.3%: 17.78 ± 0.14 0.5%: 18.80 ± 0.24	C: 18.43 ± 0.04 1%: 18.16 ± 0.07 5%: 17.47 ± 0.03 10%: 16.76 ± 0.01	C: 15.54 ± 0.76 0.1%: 17.14 ± 1.54 0.3%: 17.47 ± 1.21 0.5%: 18.65 ± 0.20	C: 15.54 ± 0.76 1%: 16.91 ± 0.42 5%: 16.79 ± 0.06 10%: 16.08 ± 0.09	C: 0.66 ±0.01 0.1%: 0.63 ± 0.04 0.3%: 0.66 ± 0.01 0.5%: 0.68 ± 0.02	C: 0.66 ± 0.01 1%: 0.67 ± 0.00 5%: 0.63 ± 0.01 10%: 0.60 ± 0.01	C: 81.57 ± 0.04 0.1%: 82.11 ± 0.57 0.3%: 82.22 ± 1.14 0.5%: 81.20 ± 0.24	C: 81.57 ± 0.04 1%: 81.84 ± 0.07 5%: 82.53 ± 0.03 10%: 83.24 ± 0.01	C: 5.02 ± 0.53 0.1%: 3.61 ± 0.07 0.3%: 4.53 ± 0 0.5%: 4.59 ± 0.60	C: 5.02 ± 0.53 1%: 3.62 ± 0.11 5%: 4.00 ± 0.86 10%: 3.80 ± 0.68	Pan-utai et al. (2020)
	C: 4.82% With algae: 5.48%										Yağmur et al. (2023)
	C: 4.63 ± 0.05 0.5%: 4.74 ± 0.02 0.75%: 4.77 ± 0.02 1%: 4.83 ± 0.02		C: 3.63 ± 0.10 0.5%: 3.52 ± 0.26 0.75%: 3.73 ± 0.04 1%:3.80 ± 0.06		-		-		C: 0.73 ± 0.01 0.5%: 0.69 ± 0.01 0.75%: 0.81 ± 0.01 1%: 0.86 ± 0.02		Dinçoğlu et al. (2024)
	C: 28.98 ± 0.04 0.5%: 29.25± 0.06 1%: 29.79 ± 0.03 1.5%: 29.90± 0.28		C: 27. 3 8 ± 0.01 0.5%: 27.16 ± 0.03 1%: 27.12 ± 0.04 1.5%: 26.88 ± 0.04		C: 38.94± 0.06 0.5%: 38.84± 0.09 1%: 38.87±0.03 1.5%: 37.87 ± 0.14		-		C: 4 .71 ± 0.04 0.5%: 4.75 ± 0.01 1%: 4.22 ± 0.04 1.5%: 5.35± 0.17		Arslan and Aksay (2022)
Isochrysis galbana	C: 3.2 ± 0.1 2%: 4.0 ± 0.1		C: 2.3 ± 0.3 2%: 2.7 ± 0.0		-		C: 87.9 ± 0.1 2%: 86.7 ± 0.0		C: 0.7 ± 0.0 2%: 1.0 ± 0.0		Matos et al. (2021)
Lipid extract *Pavlova lutheri*	C: 3.4 ± 0.1 0.25%: 3.3 ± 0.1 0.5%: 3.2 ± 0.1		C: 1.5 ± 0.1 0.25%: 1.56 ± 0.1 0.5%: 1.64 ± 0.1		C: 4.7 ± 0.2 0.25%: 4.8 ± 0.1 0.5%: 5.0 ± 0.2		C: 89.7 ± 0.1 0.25%:89.6 ± 0.1 0.5%: 89.5 ± 0.1		C: 0.7 ± 0.1 0.25%:0.7 ± 0.1 0.5%:0.7 ± 0.1		Robertson et al. (2016)

The percentages shown in the table refer to the concentration of algae biomass added to the yogurt. C: Control; (BF- Before Fermentation; AF- After Fermentation).

Table 9. pH values of yogurt fortified with algae

Species	pH								References
	Start of fermentation		End of fermentation		Start of storage		End of storage		
	C: 6.36 0.25%: 6.29 0.5%: 6.3 1.5%: 6.46		C: 4.48 0.25%: 4.5 0.5%: 4.5 1.5%: 4.5						Beheshtipour et al. (2012)
	C: 6.35 0.25%: 6.36 0.5%: 6.35 0.7%: 6.35 1.0%: 6.35		C: 4.68 0.25%: 4.48 0.5%: 4.47 0.7%: 4.46 1.0%: 4.44						Barkallah et al. (2017)
					1st day		15th day		Nourmohammadi et al. (2020)
					C: 4.28± 0.03 2%: 4.13± 0.06		C: 3.91± 0.0 2%: 3.85± 0.02		
					1st day		28th day		
	Oven-dried	Fresh	Oven-dried	Fresh	Oven-dried	Fresh	Oven-dried	Fresh	
Spirulina platensis	C: 6.18 ± 0.00 0.1%: 6.17 ± 0.01 0.3%: 6.21 ± 0.02 0.5%: 6.20 ± 0.01	C: 6.18 ± 0.00 1%: 6.17 ± 0.00 5%: 6.17 ± 0.00 10%: 6.16 ± 0.01	C: 4.39 ± 0.01 0.1%: 4.28 ± 0.02 0.3%: 4.18 ± 0.01 0.5%: 4.21 ± 0.00	C: 4.39 ± 0.01 1%: 4.37 ± 0.01 5%: 4.32 ± 0.02 10%: 4.31 ± 0.00	C: 4.13 ± 0.01 0.1%: 4.08 ± 0.00 0.3%: 4.06 ± 0.01 0.5%: 4.11 ± 0.02	C: 4.13 ± 0.01 1%: 4.15 ± 0.03 5%: 4.19 ± 0.07 10%: 4.11 ± 0.05	C: 4.13 ± 0.00 0.1%: 4.00 ± 0.01 0.3%: 4.01 ± 0.05 0.5%: 4.01 ± 0.04	C: 4.13 ± 0.00 1%: 4.09 ± 0.01 5%: 4.13 ± 0.02 10%: 4.08 ± 0.00	Pan-utai et al. (2020)
					1st day		35th days		Kazemeini et al. (2023)
					C: 4.54 ± 0.04 0.5%: 4.55 ± 0.01 1%: 4.56 ± 0.03 2%: 4.54 ± 0.02		C: 4.19 ± 0.01 0.5%: 3.95 ± 0.02 1%: 3.92 ± 0.03 2%:3.80 ± 0.01		
					1st day		28th day		Dinçoğlu et al. (2024)
					C: 5.11 ± 0.03 0.5%: 5.17 ± 0.03 0.75%: 5.50 ± 0.06 1%: 5.38 ± 0.03		C: 3.84 ± 0.02 0.5%: 3.82 ± 0.02 0.75%: 3.89 ± 0.01 1%: 4.13 ± 0.03		
					1st day		21st day		

			C: 4.57 ±0.01 2%: 4.74 ± 0.01 4%: 4.8 8%: 4.92 ± 0.01	C: 4.59 ± 0.06 2%: 4.75 ± 0.01 4%: 4.87 ± 0.02 8%: 4.88	Mohammadi-Gouraji et. al (2018)
Phycocyanin from *Spirulina platensis*			1st day	15th day	
			C: 4.53±0.02 0.5%:4.41±0.02 1%:4.19±0.01 1.5%: 4.01±0.01	C: 4.40±0.11 0.5%:4.20±0.01 1%:4.13±0.00 1.5%:3.90±0.10	Sangian et al. (2022)
Chlorella vulgaris	C: 6.36 0.25%: 6.42 0.5%: 6.45 1.5%: 6.43	C: 4.48 0.25%: 4.48 0.5%: 4.48 1.5%: 4.48			Beheshtipour et al. (2012)

The percentages shown in the table refer to the concentration of algae biomass added to the yogurt. C: Control.

Table 10. Color parameters of yogurt fortified with algae

Species	L		a		b		ΔE	References
Spirulina platensis	WN							Barkallah et al. 2017
	1st day	15th day	1st day	15th day	1st day	15th day		Nourmohammadi et al. (2020)
	C: 74.67± 0.16 2%: 54.29± 0.49	C: 71.8± 0.1 2%: 54.46± 0.19	C: -0.3± 0.31 2%: -9.07± 0.23	C: -0.76± 0.18 2%: -6.26± 0.13	C: 8.16 ± 0.16 2%: 8.69 ± 0.14	C: 4.28± 0.11 2%: 4.32 ± 0.11		
	WN							Pan-utai et al. (2020)

	C: 88.57 ± 0.28 0.5%:76.86 ± 0.05 1.0%:70.31 ± 0.25 1.5%: 65.73 ± 0.05		C: −2.12 ± 0.04 0.5%: −5.29 ± 0.27 1.0%: −4.25 ± 0.04 1.5%: -7.22 ± 0.05		C: 2.56 ± 0.08 0.5%: -3.23 ± 0.10 1.0%: -7.37 ± 0.19 1.5%: -12.54 ± 0.12		C: - 0.5%: 13.45 ± 0.18 1.0%: 20.89 ± 0.34 1.5%: 27.85 ± 0.27	Arslan and Aksay (2022)
	1st day	21th day	1st day	21th day	1st day	21th day		
Phycocyanin from *Spirulina platensis*	C: 72.53 ± 0.13 2%: 66.36 ± 0.15 4%: 62.48 ± 48 8%: 56.52 ± 0.26	C: 72.45 ± 0.01 2%: 66.88 ± 0.1 4%: 62.59 ± 0.1 8%: 56.37 ± 0.04	C: -1.93 ± 0.03 2%: -4.82 ±0.04 4%: -7.26 ± 0.08 8%: -9.91 ± 0.01	C: -1.90 ± 0.03 2%: -3.87 ± 0.04 4%: -6.45 ± 0.03 8%: -9.19 ± 0.01	C: 7.92 ± 0.02 2%: 0.47 ± 0.04 4%: -2.66 ± 0.28 8%: -6.29 ± 0.02	C: 7.48 ± 0.04 2%: 0.70 ± 0.05 4%: -2.385 ± 0.02 8%: -6.16 ± 0.01		Mohammadi-Gouraji et al. (2018)
	C: 95.09±0.27 0.5%: 93.69±0.49 1.0%: 93.48±0.10 1.5%: 92.66±0.12		C: -2.24±0.11 0.5%: -3.65±0.03 1.0%: -3.85±0.01 1.5%: -4.09±0.28		C: -0.04±0.30 0.5%: -1.05±0.01 1.0%: -1.15±0.00 1.5%: -1.43±0.04			Sangian et al. (2022)
	1st day	7th day	1st day	7th day	1st day	7th day		
Fucoxanthin from *Undaria pinnatifida*	C: 90.77 ± 0.38 FX: 90.82 ± 0.58	C: 88.52 ± 0.39 FX: 87.69 ± 0.16	C: -2.26 ± 0.08 FX: −2.03 ± 0.02	C: −1.77 ± FX: −1.83 ±	C: 5.36 ± 0.20 FX: 7.55 ± 0.26	C: 5.81 ± 0.06 FX: 8.20 ± 0.15		Wang et al. (2023)
Lipid extract Pavlova lutheri	WN							Robertson et al. (2016)

WN- Without number. The percentages shown in the table refer to the concentration of algae biomass added to the yogurt. C: Control.

Table 11. Sensory analysis of yogurt fortified with algae

Species	Scale	Color	Texture	Flavor	Acceptability	References
Spirulina platensis		WN				Akalın et al. (2009)
Spirulina platensis	0 = inconsumable; 4 = excellent Color: 0-4*2 Texture: 0-4*1 Flavor: 0-4*6	C: 8.0 0.25%:6.5 0.5%: 7.0 1.5%: 5.0	C: 3.0 0.25%:2.8 0.5%:2.8 1.5%:2.5	C: 18 0.25%: 15 0.5%: 14 1.5%: 6	-	Beheshtipour et al. (2012)
Spirulina platensis	9 (like extremely liked) to 1 (extremely disliked)	C: 9 0.25%: 7.15 0.5%: 6.25 0.75%: 5.95 1%: 4.65	C: 7.94 0.25%: 7.01 0.5%: 6.21 0.75%: 5.91 1%: 5.45	C: 7.7 0.25%: 7.54 0.5%: 6.46 0.75%: 6.22 1%: 5.45	C: 7.63 0.25%: 7.25 0.5%: 6.45 0.75%: 5.64 1%: 5.05	Barkallah et al. (2017)
Spirulina platensis	1-7	C: 6 ± 0.73 2%: 4.25 ± 1.02	C: 6.25 ± 0.64 2%: 3 .35 ± 0.67	-	-	Nourmohammadi et al. (2020)
Spirulina platensis	WN					Dinçoğlu et al. (2024)
Spirulina platensis		C: 7.64 ± 1.29 0.5%: 6.18 ± 0.60 1.0%: 5.91 ± 1.38 1.5%: 6.55 ± 0.93	-	C: 5.82 ± 1.33 0.5%: 5.09 ± 0.70 1.0%: 3.55 ± 1.04 1.5%: 2.64 ± 0.50	C: 6.55 ± 1.04 0.5%: 4.82 ± 0.40 1.0%: 3.91 ± 0.70 1.5%: 3.18 ± 0.75	Arslan and Aksay (2022)
Spirulina platensis	WN					Khaledabad et al. (2019)
Chlorella vulgaris		C: 8.0 0.25%: 7.0 0.5%: 7.0 1.5%: 5.4	C: 3.0 0.25%: 2.9 0.5%: 2.7 1.5%: 2.5	C: 18 0.25%: 16 0.5%: 16 1.5%: 12	-	Beheshtipour et al. (2012)

Algae oil (AO)	9 = like extremely, 6 = like slightly, 1 = dislike extremely				C: 7.07 ± 1.51 AO: 7.01 ± 1.45	Chee et al. (2005)
Algae oil from *Chlorella vulgaris*	WN					He et al. (2023)
Fucoxanthin (FX) from *Undaria pinnatifida*	0- 10 points	C: 8.17 ± 0.71 FX: 7.57 ± 0.98	-	-	C: 9.16 ± 1.05 FX: 9.10 ± 0.85	Wang et al. (2023)
Phycocyanin from *Spirulina platensis*	0-5 points	C: 4.40 ± 0.83 2%: 2.86 ±1.30 4%: 3.93 ± 0.70 8%: 4.46 ±0.92	-	C: 4.0 ± 1.20 2%: 3.33 ±1.63 4%: 3.13 ± 1.55 8%: 2.06 ±1.03	C: 3.86 ± 1.06 2%: 2.86 ± 1.36 4%: 3.2 ± 1.32 8%: 2.33 ± 1.35	Mohammadi-Gouraji et al. (2018)
	Texture: 5 points Flavor: 10 points	-	C: 4.35 ± 0.07 0.5%: 3.64 ± 0.07 1.0%: 3.85 ± 0.14 1.5%: 3.92 ± 0.07	C: 9.85 ± 0.14 0.5%: 9.27 ± 0.13 1.0%: 9.23 ± 0.08 1.5%: 9.00 ± 0.14	-	Sangian et al. (2022)
Algae oil from *Pavlova lutheri*	WN					Robertson et al. (2016)

WN- Without number. The percentages shown in the table refer to the concentration of algae biomass added to the yogurt. C: Control.

Table 12. Texture and syneresis data of yogurt fortified with algae

Species	Texture				STS	WHC	References
	Firmness	Cohesiveness	Consistency (g.sec)	Viscosity (g)			

Spirulina platensis	C: 0.67 ± 0.02 N 0.25%: 0.62 ± 0.04 N 0.5%: 0.58 ± 0.05 N 0.75%: 0.47 ± 0.01 N 1%: 0.47 ± 0.01 N	C: 0.32 ± 0.04 0.25%: 0.41 ± 0.03 0.5%: 0.45 ± 0.19 0.75%: 0.41 ± 0.12 1%: 0.36 ± 0.1			WN	WN	Barkallah et al. (2017)
Spirulina platensis					WN	WN	Nourmohammadi et al. (2020)
Spirulina platensis						WN	Pan-utai et al. (2020)
Spirulina platensis						C: 47.05 ± 1.11 0.5%: 45.55 ± 2.39 0.75%: 48.30 ±1.34 1%: 50.26 ± 1.52	Dinçoğlu et al. (2024)
Fucoxanthin from *Undaria pinnatifida*	1st: C: 232.86 ±11.28 FX: 145.69 ±6.26 7th: C: 77.75 ±0.79 FX: 70.94 ±2.31		1st: C: 1696.12 ±55.50 FX: 1213.35 ±63.34 7th: C: 641.16 ±24.89 FX: 710.03 ±5.57	1st: C: 433.58 ± FX:271.81 ± 13.81 7th: C: 106.58 ±7.39 FX: 118.95 ± 1.96			Wang et al. (2023)
Phycocyanin					1st 21th		Mohammadi-Gouraji

from *Spirulina platensis*				C: 32.28 ± 0.07 2%: 31.93 ± 0.01 4%: 31.84 ± 0.03 8%: 31.69 ±0.01	: 30.87 ± 0.02 2%: 29.96 ± 0.02 4%: 30.24 ± 0.51 8%: 29.36 ±0.01	et al. (2018)
Phycocyanin from *Spirulina platensis*	C: 0.31±0.00 g 0.5%: 0.27±0.07 g 1%: 0.23±0.01 g 1.5%: 0.20±0.00 g		C: 9070±30 0.5%: 8990±50 1%: 9870±30 1.5%: 91100±50	C: 6.20±0.01 0.5%: 7.77±0.13 1%: 7.59±0.06 1.5%: 7.35±0.02	C: 35.57±0.12 0.5%:31.23±0.13 1%: 31.23±0.06 1.5%: 32.93±0.02	Sangian et al. (2022)
Lipid extract *Pavlova lutheri*				WN		Robertson et al. (2016)

WN- Without number. The percentages shown in the table refer to the concentration of algae biomass added to the yogurt. C: Control.

Table 13. Bioactive compounds/effects of yogurt fortified with algae.

Species	Antioxidant Activities		References
	DPPH (%)	FRAP	

Spirulina platensis	C: 43.6 ± 1.4 0.25%: 52.41 ± 2.61		C: 0.781 0.25%: 1.35	Barkallah et al. (2017)
	1st	28th		
	C: 47.16 0.5%: 56.67 0.75% 65.22 1.0%: 77.13	C: 30.64 0.5%: 40.81 0.75%: 48.66 1.0%: 56.27	-	Dinçoğlu et al. (2024)

The percentages shown in the table refer to the concentration of algae biomass added to the yogurt. C: Control

Author Statement

G. Kovaleski: Conceptualization, Formal analysis, Investigation, Writing - Original Draft

S. P. M. Ventura: Conceptualization, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

Declaration of conflicts

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper or represent any conflict of interest.

Highlights

- Studies on yogurt and cheese fortified with algae were analyzed.
- Algae can enhance the nutritional content of yogurt and cheese.
- Algae supports the growth and viability of probiotic bacteria.
- Algae can improve firmness, cohesiveness, and water-holding capacity.