Journal of Umm Al-Qura University for Applied Sciences (2024) 10:232–243
https://doi.org/10.1007/s43994-023-00095-w

REVIEW

Unveiling the antioxidant capacity of fermented foods and food microorganisms: a focus on cyanobacteria

Taufiq Nawaz[1] · Liping Gu[1] · Shah Fahad[2,7] · Shah Saud[3] · Shah Hassan[4] · Matthew Tom Harrison[5] · Ke Liu[6] · Ruanbao Zhou[1]

Received: 25 August 2023 / Accepted: 23 October 2023 / Published online: 16 November 2023

Abstract
Cyanobacteria, which are photosynthetic prokaryotes, have gained attention in recent years for their potential health benefits. One notable property of cyanobacteria is their high antioxidant capacity, which has been attributed to various beneficial properties. Antioxidants are crucial in the human body as they help scavenge free radicals that can cause cellular damage and lead to diseases. The fermentation of food using cyanobacteria and other microorganisms has been a traditional practice for centuries and has been found to enhance the antioxidant capacity of food. This review paper aims to explore the potential of cyanobacteria in unlocking the antioxidant potential of fermented foods and food microorganisms. At the same time, the mechanisms of action of cyanobacteria-derived antioxidants and the potential health benefits of consuming fermented foods containing cyanobacteria are discussed.

Keywords Cyanobacteria · Antioxidants · Beneficial properties · Fermented foods · Food microorganisms

1 Introduction

Cyanobacteria are photosynthetic microorganisms commonly found in various freshwater bodies [93]. These microorganisms are known to produce a diverse range of metabolites, some of which possess unique properties such as antibacterial, antifungal, anticarcinogenic, immunosuppressive, and antioxidant activities [70]. Among these properties, the high antioxidant capacity of cyanobacteria stands out. Cyanobacteria have been recognized as a potential source of bioactive compounds, including antioxidants, with promising biotechnological applications in industries such as cosmetics [57] and food [80]. The search for natural antioxidants has gained significant interest due to concerns regarding the toxicity of synthetic antioxidants that contain preservatives [4]. While research on bioactive compounds in

✉ Liping Gu
Liping.Gu@sdstate.edu

✉ Shah Fahad
Shah_fahad80@yahoo.com

Taufiq Nawaz
Taufiq.Nawaz@jacks.sdstate.edu

Shah Saud
saudhort@gmail.com

Shah Hassan
janslandscaper@gmail.com

Matthew Tom Harrison
matthew.harrison@utas.edu.au

Ke Liu
ke.liu@utas.edu.au

Ruanbao Zhou
Ruanbao.Zhou@sdstate.edu

1 Department of Biology/Microbiology, South Dakota State University, Brookings, SD 57007, USA

2 Department of Agronomy, Abdul Wali Khan University Mardan, Khyber Pakhtunkhwa 23200, Pakistan

3 College of Life Science, Linyi University, Linyi 276000, Shandong, China

4 Department of Agricultural Extension Education and Communication, The University of Agriculture, Peshawar, Pakistan

5 Tasmanian Institute of Agriculture, University of Tasmania, Newnham Drive, Launceston, TAS 7248, Australia

6 Tasmanian Institute of Agriculture, University of Tasmania, Burnie, TAS 7250, Australia

7 Department of Natural Sciences, Lebanese American University, Byblos, Lebanon

cyanobacteria has traditionally focused on marine environments [100], An increasing amount of literature is investigating the antioxidant capabilities of cyanobacteria found in both freshwater and terrestrial conditions [5, 11, 15, 22, 28, 36, 47, 64, 73, 74, 79, 103]. Some of the studies have reported equal or greater antioxidant activity in cyanobacteria, emphasizing the abundance of compounds like polyphenols and carotenoids found in them [52, 64, 73, 79, 100] and/or antioxidant content [11, 36, 103] in cyanobacteria compared to eukaryotic microalgae, macroalgae, or higher plants [15, 36, 64, 73]. In this review, we focus on cyanobacteria in the context of fermented foods due to their unique and diverse contributions to this field. Cyanobacteria, known for their ability to fix atmospheric nitrogen and carry out photosynthesis, play a special role in the fermentation process by influencing taste, texture and nutritional content [95]. They are also known to produce bioactive compounds such as exopolysaccharides and antimicrobial substances, which may affect the quality and safety of fermented foods [99]. While cyanobacteria are the focus of our investigation, we also provide a brief overview of the comparable roles of other microorganisms such as lactic acid bacteria, yeasts and molds in the fermentation process. Although these microorganisms are different, they often share complementary functions. By briefly discussing their roles, we aim to provide a comprehensive understanding of the complex microbial interactions that shape the properties of fermented foods [13].

2 Overview of antioxidant compounds produced by cyanobacteria

Cyanobacteria can be found in various aquatic and terrestrial environments. They are known for their ability to produce bioactive compounds, including antioxidants, which have significant functions in diverse fields. In this discussion, we provide an overview of the antioxidant compounds produced by cyanobacteria and highlight some of the most significant findings in this field.

Marine cyanobacteria possess both enzymatic and nonenzymatic antioxidants as part of their antioxidant defense system. The low-molecular-weight nonenzymatic antioxidants derived from cyanobacteria have various applications in different industries. Due to their abundance and potential health benefits, cyanobacteria are considered a preferred alternative to synthetic antioxidants utilized in various pharmaceutical and food products [56].

One of the most well-known antioxidant compounds produced by cyanobacteria is phycocyanin. Phycocyanin is a blue-colored pigment found in the photosynthetic apparatus of cyanobacteria and similar in structure to the human bilirubin molecule. Research has indicated that phycocyanin exhibits robust antioxidant properties, and protects cells fromoxidative stress triggred by reactive oxygen species (ROS) [66].

Additionally, phycocyanin has been reported to possess anti-inflammatory, anti-cancer, and neuroprotective properties [43]. Research has validated that c-phycocyanin can be extracted from various strains of cyanobacteria using freezing and thawing methods, although the utilization of pulsed electric field treatment is limited to N. commune due to its unique cellular structure that enables extraction through this technology [16]. Carotenoids are another crucial class of antioxidant compounds synthesized by cyanobacteria. These microorganisms produce a variety of carotenoids, such as β-carotene, zeaxanthin, and astaxanthin, which are responsible for the red, orange and yellow hues of various fruits and vegetables. Scientific studies have established that carotenoids exhibit robust antioxidant activity, and protect cells from oxidative damage instigated by ROS [6]. Moreover, carotenoids have been reported to have several health benefits, including anti-inflammatory, anti-cancer, and antidiabetic properties [48, 102].

Phenolic compounds sourced from the marine environment are abundant in various natural sources, including seawater, macro- and microalgae, cyanobacteria, algae, seagrasses, and sponges. In (Table 1), extracts containing phenolic compounds from seaweed polyphenols can be classified into six structural types based on their different polymeric forms [46]. Diversity,, and their common structural features all contain phenolic hydroxyl groups [54]. According to the number and position of phenolic hydroxyl groups, they can be divided into four types: brown algae polyphenols, flavonoids, phenolic acids, and halogenated phenols, and all of them have certain antioxidant activity. Food supplements and cosmetics are among the commercial products derived mainly from extracts of phloroglucinol and phlorotannins [24].

In summary, cyanobacteria provide a diverse spectrum of antioxidant compounds with strong free radical scavenging capabilities. These compounds have been associated with various health benefits, including anti-inflammatory, anti-cancer, and neuroprotective properties. The broad spectrum of antioxidant compounds produced by cyanobacteria presents promising opportunities for the development of novel drugs, functional foods, and cosmetics. However, further research is warranted to fully explore the potential of cyanobacteria as a source of antioxidants and to elucidate the underlying mechanisms of their biological activities. Proper attribution and citation of relevant sources should always be followed to avoid plagiarism.

Table 1 Compilation of antioxidant compounds from microalgae and cyanobacteria chemicals

Compound	Mechanism	Species	Culture	Extraction	References
Pigments, peptides and vitamins	ROS	*Skeletonema marinoi*	Medium enriched with F/2, a constant temperature of 20 °C, a light exposure of 130 µmol m^{-2} s^{-1} and a light–dark cycle of 12:12 D:L	Grinding anhydrous methanol	Chen et al. [14]
Polysaccharides	Free radicals, hydroxyl radicals, and ROS	*Arthrospira platensis*	Zarrouk medium, maintaining a temperature of 30 °C, exposure to light with an intensity of 100 µmol m^{-2} s^{-1} and continuous stirring with air enriched with 1% CO_2	Use of a tangential flow ultrafiltration system with a 30 kDa molecular weight cutoff membrane	Suh et al. [86]
Polysaccharides	Free radical scavenging	*Odontella aurita*	L1 medium (618 mM), incubation at 22 °C, exposure to light intensities of 120 and 350 µmol m^{-2} s^{-1} and aeration with air supplemented with 1% CO_2	Hydrolysis of dry biomass with sulfuric acid under controlled conditions at 60 °C	Challouf et al. [12]
Sulfated polysaccharide	ROS	*Porphyridium sp.*	Using the seawater medium, maintaining a temperature of 25 °C, exposure to light with an intensity of 130 µmol m^{-2} s^{-1} and aeration with air enriched with 13% CO_2	The culture was subjected to centrifugation at 17,000*g* for 20 min, followed by filtration of the supernatant using dialysis tubing with a diameter of approximately 2.3 cm and a molecular weight cutoff of 8000	Xia et al. [98]
Pigments	Free radical scavenging	*Dunaliella salina*	Johnson medium prepared with artificial seawater (30 g L^{-1}) maintained at a pH of 7.5, exposure to 100 µmol m^{-2} s^{-1} light on a 12:12 D:L cycle and continuous aeration at a flow rate of 2 L/min1 with air	The sample was sonicated in methanol and then filtered through a 0.2 m thick Fluoropore PTFE membrane	Smerilli et al. [83]
Pigments	ROS	*Chlorella vulgaris*	The experimental setup included the use of BG-11 medium under two conditions: without and with nitrogen deficiency, with the addition of 30% NaCl, maintained at 25 °C, exposure to 130 and 1000 µmol m^{-2} s^{-1} light and aeration with air	The homogenization process involved acetone followed by filtration of the resulting supernatant through Na_2SO_4	Colusse et al. [20]
Amino acids	ROS	*Chlamydomonas hedleyi*	F/2 medium at a controlled temperature of 22 °C, exposure to 80 µmol m^{-2} s^{-1} light in a 14:8 D:L cycle, stirring with a rotary shaker and aeration with CO_2 enriched (1%) air	The dry biomass was subjected to hydrolysis with aqueous methanol (20% v/v) at a temperature of 45 °C	Gouveia et al. [30]

3 Protective role and regulation of antioxidant production in cyanobacteria

Cyanobacteria, commonly known as blue-green algae, are known to contain bioactive compounds with potential health benefits. These microorganisms are known to produce a diverse range of secondary metabolites including toxins [55]. However, some of these metabolites possess unique properties such as antibacterial, antifungal, anticarcinogenic, immunosuppressive, and antioxidant activities [67, 70]. Cyanobacteria can synthesize several secondary metabolites, including phenolic acids, flavonoids, chlorophylls, and carotenoids (Fig. 1), which have antioxidant properties and can potentially neutralize reactive oxygen species (ROS) [32].

Antioxidants refer to molecules that have the ability to counteract the negative effects of ROS and free radicals, which can lead to oxidative damage to cellular structures including lipids, DNA, and proteins [78]. One of the primary mechanisms of antioxidants in cyanobacteria is scavenging ROS. Cyanobacteria are exposed to high levels of ROS during photosynthesis due to the production of singlet oxygen and superoxide radicals [34]. In photosynthetic organisms like cyanobacteria, ROS is generated as a result of photosynthetic electron transport. The ability of cyanobacteria to rapidly sense ROS and defenses in response to changing environmental conditions, such as sudden changes in light intensity, is crucial for their survival [44]. Tocopherols have been found to protect cyanobacteria from oxidative stress caused by high light and heat [77].

Another mechanism of antioxidants in cyanobacteria is the modulation of gene expression. Antioxidants can regulate the expression of genes involved in the synthesis of antioxidant enzymes and other stress-response proteins. For instance, studies have shown that carotenoids can upregulate the expression of genes encoding antioxidant enzymes such as superoxide dismutase and catalase in the cyanobacterium *Synechocystis sp*. PCC 6803 [87]. Maintaining a proper balance between ROS and antioxidant defenses is crucial for optimal cellular function and the ability to respond to various stimuli [40].

These findings suggest that antioxidants can enhance the cellular antioxidant capacity of cyanobacteria by regulating gene expression. In addition to their role in protecting cyanobacteria from environmental stressors, antioxidants also have potential applications in biotechnology and medicine. For example, carotenoids such as astaxanthin and zeaxanthin have been shown to possess antioxidant, anti-inflammatory, and immunomodulatory properties [53, 97]. Due to their potent antioxidant properties, astaxanthin is considered as a potential defender against various diseases in many organisms, including cardiovascular diseases [65]. Similarly, tocopherols have been found to exhibit anti-inflammatory and neuroprotective properties, and may have potential applications for treating Alzheimer's disease [9, 75].

Overall, antioxidants play important roles in protecting cyanobacteria from environmental stressors such as high light and oxidative stress. These molecules can scavenge ROS and modulate gene expression, thereby enhancing the cellular antioxidant capacity of cyanobacteria. In addition, antioxidants have potential applications in biotechnology and medicine. Further research is needed to elucidate the mechanisms of antioxidants in cyanobacteria and explore their potential applications in various fields.

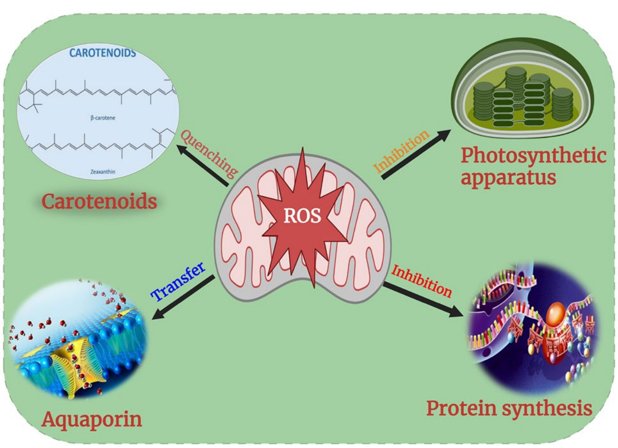

Fig. 1 Cyanobacteria helps to mitigate the negative effects of ROS by accumulating carotenoids, and the use of aquaporins may facilitate the transfer of ROS from the photosystem to other cellular regions. The photosynthetic apparatus can be destroyed and protein synthesis inhibited by excessive ROS

4 Fermentation and antioxidant capacity

The traditional practice of fermentation is a worldwide technique used to process and preserve food while improving, while also enhancing the nutraceutical properties of the food. In response to the increasing demand for healthy and sustainable diets, it is crucial to develop innovative food production methods that promote human health and environmental sustainability. Recently, scientific studies have focused on fermented goods derived from microalgae. These microalgae are deemed to be potential food sources due to their rich stores of beneficial compounds. The nutritional value, versatile metabolism and diverse functionality of microalgae make them suitable substrates for lactic acid bacteria (LAB) and yeasts during the fermentation process [27].

Research has been conducted on the potential of lactic acid fermentation on various types of algae, providing opportunities for the production of fermented food products utilizing these resources. Some studies have specifically investigated the use of Spirulina as a sole substrate for lactic acid fermentation [92]. To develop probiotic-based products, researchers investigated the use of solely Spirulina biomass in lactic acid fermentation. The fermentation lasted 48 h and resulted in a significant increase in the concentrations of *Lactobacillus plantarum* and lactic acid. The fermentation process also resulted in an augmentation of in vitro antioxidant activities, total phenolic content, and digestibility [60].

Fermentation of Spirulina led to a similar total phenolic content and in vitro antioxidant activity as untreated biomass, while protein fragmentation and free methionine content increased linearly with fermentation time. Probiotic-based products have been prepared using various combinations of lactic acid bacteria, Bacillus strains, and their mixtures during the fermentation of Spirulina. Positive effects on flavor, nutrition, or bioactivity were observed for lactic acid bacteria and Bacillus strains [101]. Another study showed that the fermentation of A. maxima with *L. plantarum* led to an increase in total antioxidant capacity and beta-carotene profile. This increase was suggested to be responsible for the higher levels of brain-derived neuroprotective factor observed compared to the untreated control [18].

Fermenting Arthrospira platensis (cyanobacteria) biomass has been found to be a promising source of antioxidants that exhibit intracellular activity, reducing levels of intracellular reactive oxygen species (ROS) and preventing oxidative damage to lipids. Fermented Arthrospira platensis has been shown to have higher protein bioavailability due to increased non-protein nitrogen content compared to non-fermented biomass. Additionally, the fat content of fermented Arthrospira platensis is lower, while the levels of other nutrients remain unchanged. Moreover, Arthrospira platensis is free of pathogenic bacteria after fermentation and has a lower pH, suggesting extended longer shelf life. These features make it a potential contender for use as a nutritional supplement or as an ingredient in various food products [41].

In conclusion, the ancient technique of fermentation has regained interest as a method of improving the nutraceutical properties of food while preserving it. With the growing demand for healthy and sustainable diets, innovative food production practices are crucial for promoting human health and environmental sustainability. Microalgae, such as *Arthrospira platensis*, *Chlorella vulgaris*, and *Dunaliella salina*, have emerged as promising food sources due to their nutritional value and flexible metabolism. Lactic acid fermentation has been tested on various types of algae, including microalgae and macroalgae, providing a way to create fermented food products. Probiotic-based products developed exclusively using Spirulina biomass for lactic acid fermentation have shown enhanced antioxidant activity, total phenolic content, and digestibility. Similarly, fermented *Arthrospira platensis* has shown potential as a nutritional supplement or ingredient in foods due to its higher bioavailability of proteins lower, and improved shelf life. Overall, fermented algae-based fermented products offer a novel approach to developing functional foods that meet the needs of a growing health-conscious population.

5 The role of cyanobacteria in the fermentation process and their impact on the sensory and nutritional properties of fermented foods

Cyanobacteria are well-known for their ability to fix atmospheric nitrogen and generate organic acids through photosynthesis. During the process of fermentation, cyanobacteria can contribute to the production of lactic acid, acetic acid, and other organic acids, which play a crucial role in the preservation and sensory quality of fermented foods. These organic acids can inhibit the growth of pathogenic bacteria, enhance the flavor and aroma of fermented foods, and impart the characteristic sour taste of fermented products [21].

Cyanobacteria display several fermentation pathways that yield various by-products, such as CO_2, H_2, formate, acetate, lactate, and ethanol. Fermentation is a constitutive process in all examined species, with all the enzymes required for the fermentative pathways being present in photoautotrophically grown cells. Additionally, certain cyanobacteria have the ability to use elemental sulfur as an electron acceptor, which results in higher ATP yields during fermentation. However, sulfur respiration is unlikely in most cases. Currently, oxygen and elemental sulfur are the only known electron acceptors for chemotrophic metabolism in cyanobacteria. Although ATP yields during fermentation are lower than those during aerobic respiration, calculations suggest that the low maintenance requirements of these cyanobacteria mean that the ATP produced during fermentation is likely sufficient [85].

Cyanobacteria can significantly influence the sensory properties of fermented foods, including flavor, aroma, and texture. The flavor and aroma of fermented foods are mainly determined by the production of organic acids, esters, alcohols, and other volatile compounds during the fermentation process. Cyanobacteria can contribute to the production of these compounds, enhancing the overall flavor and aroma of the final product.

For instance, yogurt, a widely consumed fermented dairy product, is made using lactic acid bacteria. These bacteria play a crucial role in yogurt production by producing lactic acid, which lowers the pH and leads to the coagulation of milk proteins. In addition to lactic acid, the metabolites produced by these bacteria, including carbonyl compounds, non-volatile or volatile acids, and exopolysaccharides, are important factors that impact the quality of yogurt [58]. Similarly, in the production of sourdough bread, lactic acid bacteria and yeast are used as starter cultures, which produce carbon dioxide, ethanol, and acetic acid. These compounds contribute to the flavor, texture, and aroma of the final product [91].

Cyanobacteria can also have a significant impact on the nutritional properties of fermented foods. During the fermentation process, they can increase the bioavailability of nutrient, such as zinc, and calcium by reducing the levels of anti-nutrients like phytate and oxalate [90]. This can improve the nutritional quality of the final product and enhance its health benefits. Microalgae synthesize a variety of compounds from different metabolic pathways, such as amino acids, fatty acids, lycopene, polysaccharides, steroids, carotenoids, lectins, polyketones, toxins, etc. Some of these are shown in Fig. 2.

Cyanobacteria are crucial in the fermentation process of different food products, such as sorghum porridge and milk-based products like yogurt. For instance, cyanobacteria can enhance the bioavailability of iron in fermented sorghum porridge by up to four times by reducing the levels of phytate, a compound that can bind to iron and inhibit its absorption in the body [88]. Similarly, cyanobacteria can also increase the bioavailability of calcium in fermented milk products. Calcium is a vital mineral essential for bone health and is found in high concentrations in milk. However, the bioavailability of calcium in milk is relatively low as it is bound to casein, a milk protein. Cyanobacteria can produce lactic acid during the fermentation process, which can lower the pH of the milk and cause casein to denature, releasing calcium and making it more available for absorption in the body [26]. Additionally, cyanobacteria in fermented milk products can also produce folate, an important B-vitamin necessary for cell growth and development [29].

In summary, cyanobacteria play a significant role in the fermentation process of various foods, including dairy products, cereals, and beverages. They contribute to the production of organic acids, enhance the flavor and aroma of fermented foods, and improve the bioavailability of nutrients. The use of cyanobacteria as starter cultures in the production of fermented foods has been shown to positively impact the sensory and nutritional properties of the final product. However, further research is required to fully comprehend the mechanisms by which cyanobacteria contribute to the fermentation process and explore potential new applications for these microorganisms in the food industry.

6 Potential applications of cyanobacteria in the development of functional foods and nutraceuticals

Cyanobacteria, also known as blue-green algae, are photosynthetic bacteria that play a crucial role in ecosystems. They have been recognized as a potential source of bioactive

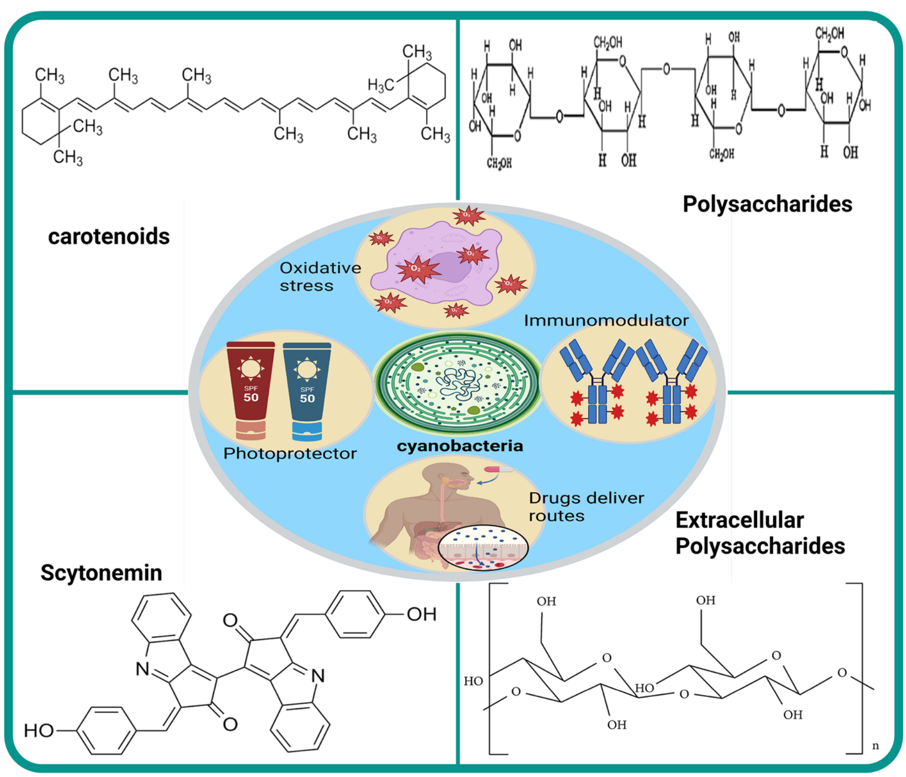

Fig. 2 Molecular structure of microalgae-derived compounds for a variety of biotechnology applications (modified from Martinez-Ruiz et al. [51])

compounds for the development of functional foods and nutraceuticals. Cyanobacteria are rich in proteins, lipids, carbohydrates, vitamins, and pigments, making them a valuable resource. One of their main advantages is their ability to produce various bioactive compounds such as phycobiliproteins, carotenoids, polyunsaturated fatty acids, and polysaccharides, which have health benefits. For example, phycocyanin, a blue pigment found in cyanobacteria, has been shown to possess antioxidant, anti-inflammatory, and immunomodulatory properties, making it a potential candidate for functional foods and nutraceuticals [38].

Cyanobacteria are also a good source of proteins with amino acid composition. Spirulina and Aphanizomenonflos-aquae are two cyanobacteria species extensively studied for their protein content. Spirulina, in particular, has a protein content of up to 70%, which is higher than most plant and animal-based proteins, making it an excellent candidate for protein-rich functional foods and nutraceuticals [76, 89]. Thus, cyanobacteria can serve as a source of omega-3 fatty acids in the development of functional foods and nutraceuticals.

The balanced composition and rich nutritional content of Spirulina platensis make it a promising ingredient for functional foods, with various potential health benefits. Additionally, microalgae and their biopolymers are being recognized as important components for structuring food products [94].

Similarly, research has shown that the polysaccharide "sulfated exopolysaccharide" found in Lyngbya sp. exhibits antitumor properties [39]. Cyanobacteria are considered a potential source of bioactive compounds for the development of functional foods and nutraceuticals. They are rich in proteins, polyunsaturated fatty acids, vitamins, and pigments, all of which offer various health benefits. However, the utilization of cyanobacteria as a source of bioactive compounds in functional foods and nutraceuticals is still in its early stages, and further research is needed to fully understand their potential in this field.

7 Potential synergistic effects of combining cyanobacteria with other food microorganisms in fermentation processes

Cyanobacteria are photosynthetic microorganisms known for their ability to produce diverse bioactive compounds with potential health benefits, including antioxidants, polysaccharides, and phycobiliproteins. In recent years, fermentation processes involving cyanobacteria have gained significant attention due to their potential to enhance the nutritional and functional properties of foods. However, the use of cyanobacteria in fermentation processes is limited by their low tolerance to environmental stresses, such as changes in temperature, pH, and salinity. To address these limitations and improve the efficiency of cyanobacterial fermentation, researchers have explored the potential synergistic effects of combining cyanobacteria with other food microorganisms, such as lactic acid bacteria (LAB), yeast, and fungi.

LAB are commonly used in food fermentation due to their ability to produce lactic acid, which can lower the pH and inhibit the growth of harmful bacteria. When combined with cyanobacteria, LAB can enhance the production of bioactive compounds, such as exopolysaccharides (EPS) and phycobiliproteins, through symbiotic interactions. For instance, a study by Calder [10] demonstrated that co-culturing *Synechococcus sp*. and *Lactobacillus plantarum* resulted in a significant increase in EPS production, as well as improved antioxidant and antibacterial activities compared to monoculture.

Yeasts and fungi are commonly used in food fermentation and have been shown to enhance the nutritional and functional properties of fermented foods. When combined with cyanobacteria, yeasts and fungi can improve the texture, flavor, and aroma of fermented foods, as well as increase the production of bioactive compounds. For example, a study by Hayashi et al. [37] demonstrated that co-culturing *Spirulina platensis* and Saccharomyces cerevisiae resulted in a significant increase in γ-aminobutyric acid (GABA) production, which has been associated with various health benefits, including anti-inflammatory and anti-anxiety effects.

Spirulina, a photosynthetic cyanobacterium with wide distribution in nature, has been used as a nutritional supplement for many centuries due to its high nutritional value. It is a rich source of various vitamins, minerals, 78% proteins, 4–7% lipids, carbohydrates, and natural pigments. The consumption of Spirulina has been associated with several health benefits, including corrective properties against cancer, hypertension, hypercholesterolemia, diabetes, and anemia. Recent research has demonstrated that extracellular products produced by Spirulina platensis can enhance the growth of probiotic microorganisms, such as *Lactococcus lactis*, *Streptococcus thermophilus*, *Lactobacillus casei*, *Lactobacillus acidophilus*, and *Lactobacillus bulgaricus* [33]. This paper will focus on the prebiotic effects of certain blue-green algae on probiotic microorganisms.

The use of co-culture systems combining microalgae and bacteria has been investigated to mitigate contamination risks associated with axenic cultures. Co-cultures have shown to lead to higher biomass yields and synthesis of active compounds. Probiotic microorganisms have been identified as suitable co-culture partners due to their beneficial effects on health. Several studies have demonstrated that algae are prebiotics that can enhance the performance of probiotics. Additionally, the use of algae and probiotics together has been found to improve the microbiota, promote gut health, and increase yields in aquaculture, specifically in fish, shrimp, and mussels [68].

There are more than 600 species of macroalgae used in food products, categorized based on their color [45, 69]. Extracted bioactive compounds from macroalgae, particularly from brown, red, and green types, have demonstrated potential in preventing and treating neurodegenerative diseases [2, 19]. Phytosterols, including fucosterol, have been shown to have health benefits such as anticancer, antidiabetic and neuroprotective effects etc. [35].

Furthermore, it has been discovered that pigments extracted from different types of macroalgae exhibit antioxidant properties as demonstrated by in vitro and in vivo tests [25, 42, 71, 72]. Carotenoids, including zeaxanthin, beta-carotene, canthaxanthin, and nostoxanthin, are abundant in cyanobacteria and are valuable ingredients in various products such as food supplements, colorants, food additives, and animal feed. Cyanobacteria-derived carotenoids are commonly available in tablet, granule, and capsule forms, and their production is increasing. For instance, supplements such as β-carotene, riboflavin, vitamin B12, and thiamine are obtained from cyanobacteria like Spirulina [3, 23]. Cyanobacteria are also utilized as a source of minerals, amino acids, proteins, complex sugars, carbohydrates, phycocyanin, active enzymes, essential fatty acids, and chlorophyll, and are used as whole food or dietary supplements in Fig. 3 [49].

Cyanobacterial biomass is commonly used as a source for whole dietary supplements, in contrast to extracts used in pharmaceutical production [50]. One popular supplement is astaxanthin, a ketocarotenoid known for its potent antioxidant properties. Astaxanthin, along with other carotenoids,

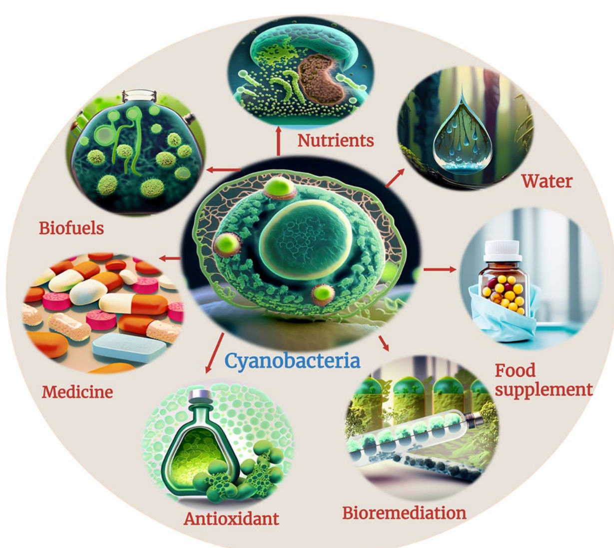

Fig. 3 Overview of the potential of cyanobacteria in various research areas

plays a crucial role in preventing cell damage from photooxidation. Haematococcuspluvialis is a known producer of astaxanthin, which has been found to be a potent inhibitor of proteases used in the treatment of various diseases, including human immunodeficiency virus (HIV) disease, the virus responsible for acquired immunodeficiency syndrome (AIDS) [31, 62, 80].

In general, the combination of cyanobacteria with other food microorganisms in fermentation processes has shown promising results in enhancing the nutritional and functional properties of fermented foods. However, further research is needed to understand the mechanisms underlying these synergistic effects and to optimize the fermentation conditions for maximum efficiency. Nevertheless, the potential benefits of combining cyanobacteria with other food microorganisms in fermentation processes make this an exciting area of research with significant implications for the development of functional foods with improved health benefits.

8 Future prospects and challenges in utilizing cyanobacteria for food and health applications

Cyanobacteria possess metabolic processes, including carotenogenesis and photosynthesis that result in the production of valuable primary and secondary metabolites. In primary metabolites, such as antioxidants, proteins, and lipids, are essential for developmental processes like growth, cell division, and reproduction, and can be re-engineered for biotechnological products like biofertilizers, dyes, bioplastics, and food supplements [1, 17, 59, 61, 63]. On the other hand, secondary metabolites are not directly involved in normal cyanobacterial growth, reproduction, or development, as they are primarily produced for defensive purposes [7].

Another potential application of cyanobacteria is as a source of bioactive compounds for health promotion. Cyanobacteria can synthesize bioactive compounds like phycocyanin, carotenoids, and polysaccharides, which possess antioxidant, anti-inflammatory, and immune-enhancing properties [8, 82]. These compounds have been investigated for their potential health benefits in conditions such as cancer, cardiovascular disease, and diabetes [96].

However, the use of cyanobacteria for food and health applications also comes with challenges and concerns. One major concern is the potential production of toxins by certain cyanobacterial strains in Fig. 4, such as microcystins, which can cause liver damage and other health issues [81, 84]. Therefore, careful selection and cultivation of non-toxic strains, as well as monitoring of toxin production during cultivation and processing, are crucial for food and health applications.

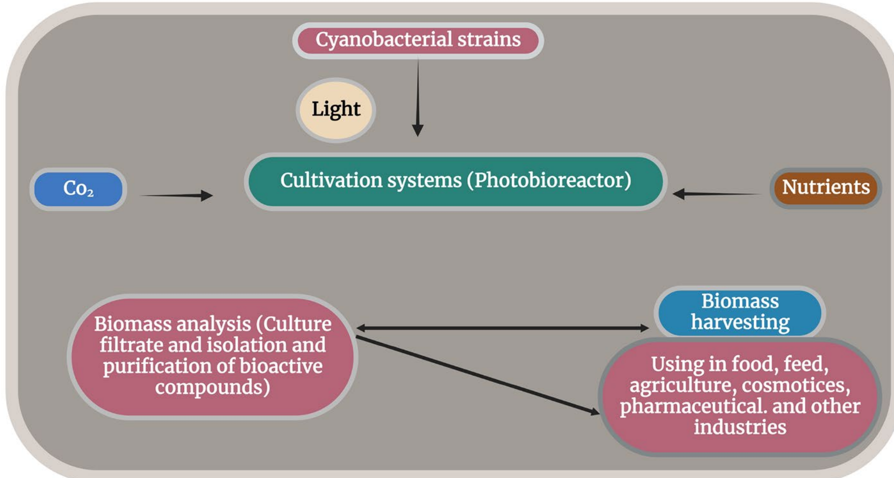

Fig. 4 Cyanobacterial strains' culture, harvesting, and downstream use

In conclusion, cyanobacteria hold promise for food and health applications as a sustainable and bioactive source of protein and functional compounds. However, addressing safety issues and scalability limitations is important. Further research and development are needed to optimize cyanobacterial cultivation, processing, and application for food and health purposes.

9 Conclusion

In conclusion, cyanobacteria, with their remarkable antioxidant properties and various health benefits, have proven to be a promising resource for improving the nutritional quality of fermented foods and dietary supplements. Their ability to increase antioxidant levels, coupled with potential anti-inflammatory and immunomodulatory effects, underscores their importance in promoting health and preventing disease. While further research is essential to elucidate the mechanisms underlying cyanobacteria-derived antioxidants and their full spectrum of potential health benefits, existing evidence supports their use as functional food ingredients and dietary supplements. This paper highlights the compelling prospects of cyanobacteria and highlights the importance of continued investigation to realize their full potential to promote well-being and mitigate health risks.

Author contributions Conceptualization TF, LG, RZ, SS and SF, Data; SS, SF, MTH, and KL, writing—original draft, TF, SS, and SF, writing—review and editing TF, SF, SS.

Funding No funding was obtained for this study.

Availability of data and materials Not applicable.

Declarations

Competing interests The authors declare that they have no competing interests.

Ethical approval Not applicable.

Consent to participate All authors are agreed to contribute to this study.

Consent to publish Not applicable.

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