Research Article **Open Access**

Formulation and evaluation of a spirulina-enriched popsicle using indigenous Indian blackberry: Nutrient density and seed waste valorisation

Radhika Hedaoo[1]*, Suchetana Chatterjee[2], Anushthi Singh[1], Mansi Patil[3]

[1]M.Sc Nutrition and Dietetics Program; Symbiosis School of Culinary Arts and Nutritional Sciences, Symbiosis International (Deemed University), Pune, India; [2]M.Sc Nutrition and Dietetics Program; Symbiosis School of Biological Sciences, Symbiosis International (Deemed University), Pune, India; [3]Asha Kiran Hospital, Pune, India

***Corresponding Author**: Radhika Hedaoo, Assistant Professor, M.Sc Nutrition and Dietetics Program; Symbiosis School of Culinary Arts and Nutritional Sciences, Symbiosis International (Deemed University), Pune, India.

Submission Date: September 24th, 2025, **Acceptance Date:** October 26th, 2025, **Publication Date:** November 3rd, 2025

Please cite this article as: Hedaoo R., Chatterjee S., Singh A., Patil M. Formulation and evaluation of a spirulina-enriched popsicle using indigenous Indian blackberry: nutrient density and seed waste valorisation. Functional Food Science 2025; 5(11): 567 – 583. DOI: https://doi.org/10.31989/ffs.v5i11.1795

ABSTRACT

Background: Spirulina (*Arthrospira platensis*), a protein-rich microalga, has gained recognition as a functional ingredient due to its potent antioxidant and immune-boosting properties. While widely studied as a dietary supplement, its integration into culturally relevant, ready-to-consume frozen desserts remains underexplored, especially in the Indian context.

Objective: This study aimed to formulate a nutrient-dense popsicle by combining spirulina with Indian blackberry (*Syzygium cumini*), and to evaluate its sensory acceptability, nutritional profile, and market feasibility in comparison with commercially available fruit popsicles.

Methods: Using a standardized food product development protocol, spirulina-enriched Indian blackberry popsicles were developed and subjected to sensory evaluation using a 9-point hedonic scale (n=20), and product profiling was checked by trained panelists (n=5). Proximate and micronutrient analyses were performed in accordance with FSSAI standards. A paired t-test compared the experimental popsicles with a control (Indian blackberry flavoured commercially and popularly available Popsicle). In line with a zero-waste approach, deseeded blackberry seeds were collected, cleaned, shade and oven-dried (50 °C, 45 min), ground, processed into powder, and retained as a functional by-product for future value-added applications.

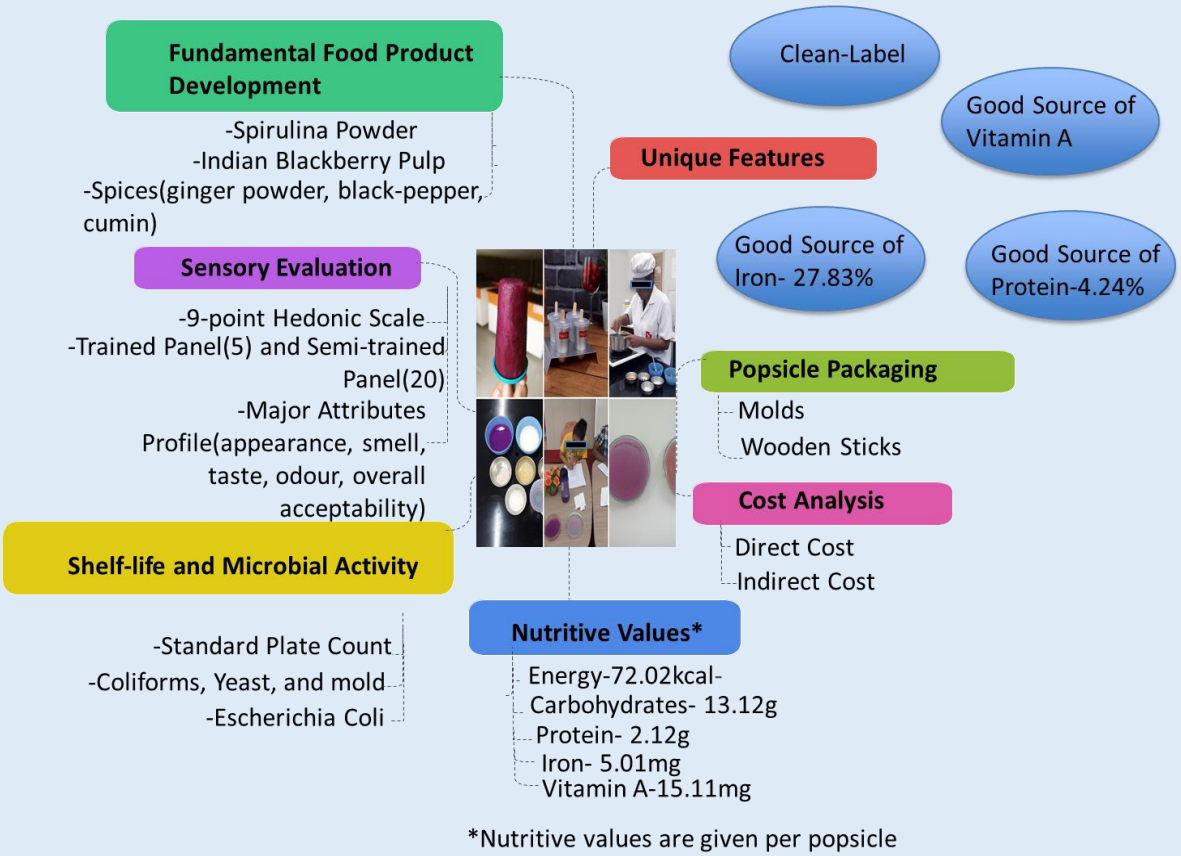
Results: The experimental spirulina popsicle achieved an overall sensory acceptability score of 85%, significantly outperforming the control at 68% ($p \leq 0.05$). Nutritionally, the product delivered 2.12g protein, 15.11 µg Vitamin A,

5.01 mg iron, and was 55% lower in sugar compared to the control. The processed blackberry seeds yielded 4 g of seed powder per 20 g of seeds, as a functional byproduct.

Novelty: To our knowledge, this is the first study from India to formulate and evaluate a spirulina-enriched frozen dessert utilizing an indigenous fruit base. By integrating sensory acceptability with nutritional profiling, the work advances functional food innovation within the frozen fruit-based confection category, while simultaneously addressing sustainability through a zero-waste approach, yielding a value-added ingredient from the seeds of Indian blackberry. The spirulina-enriched fruit base popsicle shows clear nutritional superiority over the commercial control, establishing its novelty as a functional frozen dessert offering a healthier, low-sugar alternative while simultaneously introducing 2.12 g of protein and significant levels of vitamin A, vitamin C, iron, and magnesium, all absent in the commercially available control.

Conclusion: The developed popsicle offers a clean-label, low-sugar alternative to conventional frozen treats, with the added advantage of micronutrient enrichment and seed-waste valorisation. The product represents a promising addition to the growing category of culturally tailored functional foods that align with zero-waste and nutritional security goals.

Keywords: Spirulina, Indian blackberry, functional popsicles, nutrient density, clean label, sensory evaluation, superfoods, food innovation, seed waste valorisation, frozen fruit based confection.



Graphical Abstract: Innovation in functional plant-based popsicle: nutritional and sensory assessment of spirulina-enriched Indian blackberry popsicles

INTRODUCTION

Frozen fruit-based confections have been enhanced and innovated as desserts that deliver health benefits beyond basic nutrition due to the rising demand of health-conscious consumers. According to Grand View Research, the Indian vegan Popsicle market generated USD 2.2 million in 2024, with projections to reach USD 5.5 million by 2030 at a CAGR of 17.3% (2025–2030) [1]. Among flavour segments, fruit-based variants accounted for the highest revenue share in 2024, while exotic and tropical flavours are projected to exhibit the fastest growth rate during the forecast period. The growing demand for functional foods that offer health benefits beyond basic nutrition has opened new frontiers in food product innovation. With rising health consciousness, especially among younger consumers, there is a clear shift toward foods that combine taste, convenience, and nutritional value. Frozen desserts are no longer just indulgences; they are increasingly being reformulated as delivery vehicles for functional ingredients. Among these, ice pops and fruit-based frozen snacks are gaining popularity for their affordability, flavour appeal, and suitability to tropical climates like India's [1-2].

The increasing prevalence of lifestyle-related diseases and widespread micronutrient deficiencies has heightened global interest in functional foods, defined as foods that offer health benefits beyond basic nutritional value [3]. One such functional ingredient is spirulina (Arthrospira platensis), a nutrient-rich cyanobacterium acknowledged by the Food and Agriculture Organization (FAO) as a sustainable “superfood.” Spirulina is an abundant source of high-quality protein (60–70%), essential amino acids, B-complex vitamins, provitamin A, and minerals such as iron, calcium, and magnesium. Additionally, it contains γ-linolenic acid and bioactive pigments, such as phycocyanin, which exhibit antioxidant, anti-inflammatory, and immunomodulatory properties [4-5].

It contains over 60% high-quality protein and is rich in essential amino acids, B-vitamins, iron, and key bioactive compounds such as phycocyanin, β-carotene, and γ-linolenic acid (GLA) [5-6]. These compounds have been studied for their antioxidant, anti-inflammatory, immune-modulatory, and even neuroprotective effects [5-7]. Phycocyanin, in particular, is a potent scavenger of free radicals and plays a role in protecting neural and immune cells from oxidative stress [6,7]. Studies have also highlighted spirulina’s potential in managing conditions such as anemia, malnutrition, and metabolic disorders through its bioavailability and nutrient density [5-7]. There are over 35 species of spirulina; however, S. platensis and S. maxima are the most commonly used for food. The World Health Organization (WHO) says that spirulina is the most nutritious and healthy food on the planet [8]. Spirulina is 63% protein and is also considered the best natural source of vitamin A in the world [9]. It has an abundance of chlorophyll and other beneficial phytochemicals, like beta-carotene and phytocyanins, while also containing many of the necessary amino acids for bodily function. Spirulina also contains many other macronutrients and micronutrients, as well as the important fatty acid γ-linolenic acid (GLA) and small amounts of polysaccharides [10]. Spirulina is an excellent source of good bacteria for your gut, especially *Lacticaseibacillus* spp. (formerly *Lactobacillus*) and *Bifidobacterium* spp. Spirulina has shown promise as a probiotic ingredient in milk-based biscuits, supported by several in vitro studies [8,11]. Sensory evaluations and consumer trends suggest growing acceptance of microalgae-based foods, including spirulina, in everyday diets. Its safety is well established, with the U.S. Food and Drug Administration (FDA) recognizing spirulina as GRAS (Generally Recognized as Safe) [12]. Recent research on Indian Blackberry (*Syzygium cumini*) highlights its potential as a functional food ingredient, given its high levels of anthocyanins, phenolics, and natural antioxidants. These compounds provide health

benefits, including antidiabetic, antihyperlipidemic, and anti-inflammatory properties, making Indian blackberry valuable in the formulation of functional and nutraceutical food products.

The dark algal color and earthy taste often pose challenges in its consumption in daily foods. However, Indigenous fruits, such as the Indian blackberry (*Syzygium cumini L.*), complement spirulina's nutrient profile as they are rich in anthocyanins, vitamin C, and phenolic compounds known for their anti-diabetic, cardio-protective, and antioxidant effects [13]. Including spirulina with nutrient-dense local fruits grants an opportunity to improve functional, culturally acceptable, and sustainable food innovations. Novel food delivery designs, including ice candies, frozen popsicles, beverages, and smoothies, are predominantly likely as they are appealing to children and adolescents, a population often resistant to conventional health supplements. These product designs are also cost-effective, sensory-appealing, and well-suited to tropical climates as found in India.

However, despite the growing interest in functional foods, the integration of spirulina with indigenous fruits into culturally relevant frozen products remains largely unexplored. This study addresses that gap by formulating a low-sugar, nutrient-dense popsicle using Syzygium cumini pulp and spirulina, achieving superior sensory performance over commercial products. Moreover, the zero-waste valorization of fruit seeds into a bioactive, value-added ingredient adds a sustainability dimension that is less reported in frozen confection development.

Hence, the enrichment of spirulina into Indian blackberry-based ice candies and beverages denotes a practical strategy to address nutritional deficiencies, augment the value of indigenous produce, and propagate the functional food entrepreneurship in local communities.

Combining Indian Blackberry and spirulina leverages their complementary nutritional and functional attributes, with Indian blackberry acting as an ideal vehicle to mask spirulina's flavour and enhance consumer acceptance while boosting the overall antioxidant and protein content. The synergistic blend improves both the nutritional density (especially protein, antioxidants, and minerals) and sensory appeal. This synergistic approach supports the development of innovative functional food products that improve nutritional security and promote health and wellness. Moreover, little research has explored this synergy in frozen functional confection formats that also align with zero-waste and clean-label food trends. The research not only addresses nutritional fortification and taste optimization but also explores seed waste valorisation from Indian blackberry, supporting sustainable food innovation in the Indian context. While spirulina has been extensively investigated as a dietary supplement, its application in culturally appropriate, ready-to-consume frozen confections has not been explored. This study bridges that gap by combining spirulina with *Syzygium cumini* to create a nutrient-dense, low-sugar popsicle that not only achieves high sensory acceptability but also integrates sustainability by valorizing fruit seeds into functional by-products. Such an approach represents a novel direction in functional food development, aligning nutritional enhancement with waste reduction and cultural relevance.

AIMS AND OBJECTIVES

1. To formulate a functional popsicle by incorporating spirulina with indigenous Indian blackberry (*Syzygium cumini*), while ensuring desirable sensory and physicochemical attributes.
2. To evaluate the nutrient density profile of the formulated popsicle, with emphasis on macro- and micronutrient enhancement contributed by spirulina and Indian blackberry.
3. To assess the overall consumer acceptability of the spirulina-enriched, indigenous fruit-based popsicle as a sustainable functional food product.
4. To valorize Indian blackberry seed waste in alignment with a zero-waste product development approach.

MATERIALS AND METHODS

The experimental design study was conducted to develop Indian Blackberry ice-popsicles enriched from spirulina. The methodology involved selection standardisation and preparation of raw materials, processing of raw materials, preparation of ice popsicles and its nutritional and sensory evaluation.

Raw Materials: Fresh Indian Blackberry, called Java Plum or *Syzygium cumini* (L.) Skeels (Family: Myrtaceae) was the base ingredient, along with Green Spirulina powder Arthrospira platensis Gomont (Family: Microcoleaceae) procured from an organic store, sugar, black salt, ginger powder, and cumin powder were procured from the local market. Stainless steel moulds were used for setting the Popsicle.

The Rationale for Selecting Ingredients*:* The main ingredients selected for making the popsicles were Indian blackberry and Spirulina. Since spirulina has an odd green color and an unusual taste, the main challenge was to make the popsicle in a way that masks both the color and the taste. As spirulina is considered a novel food, scientific studies have shown that consuming 2 grams of spirulina provides the equivalence of 5 servings of fruits and vegetables recommended by the RDA [14]. The most suitable food vehicle chosen was Indian blackberry juice for its natural dark violet color, which was ideal for masking the algal green color of spirulina. Recent studies have demonstrated that Indian blackberry has several pharmacological effects, such as antibacterial, antifungal, anti-inflammatory, anti-allergic, and chemoprotective. The phytochemicals in its seeds have been highly successful, and they are using them in various therapeutic methods and applications. [15]. The fruit has been traditionally recommended for treating different conditions, including ulcers, allergies, diabetes, and inflammation. [16]. Cumin, ginger powder, black pepper, and black salt were selected as functional ingredients due to their rich micronutrient profiles. Table 1 presents the composite nutrient profiles of spirulina and Indian blackberry.

Table 1: Composite Nutrient Profile of Spirulina and Indian Blackberry

S.No.	Nutrients	Spirulina	Indian Blackberry
1.	Energy (Kcal)	361.0	227
2.	Carbohydrate (grams)	16.0	10.64
3.	Total Sugars (grams)	3.1	7.61
4.	Protein (grams)	66.0	0.92
5.	Total fat (grams)	3.0	0.63
6.	B carotene (mg)	25	52.32
7.	Sodium (mg)	1150.0	1.21
8.	Iron (mg)	175	0.63
9.	Vitamin A (mg)	300	2.62
10.	Vitamin C (mg)	-	19.45
11.	Potassium (mg)	1700	205
12.	Magnesium (mg)	-	30.90

*Nutrition profile values for Indian Blackberry have been taken from IFCT [17], and values for spirulina have been taken from the commercial spirulina powder label.

Approvals: Approvals for the study were taken via the Institutional Research Advisory Committee, Symbiosis International (Deemed University). Informed consent was obtained from proposed panelists for the

laboratory protocol for sensory evaluation before the food product development protocol was initiated. Allergen information was given to all panelists.

Study Locale: Nutrition laboratory, Symbiosis International (Deemed University), Pune, India.

Formulation and Standardization of the Product: USDA defines "Standardized recipe *as one which has been tried, adapted, and retried to produce the same yield and taste whenever the same equipment, procedures, and quantity and quality of ingredients are used."* [18]. Recipe standardization was carried out over eight trials, where ingredient proportions and spice blends were systematically adjusted; the final formulation was selected based on the highest sensory scores for taste, color, and texture.

Steps Involved in Making Spirulina 'Indian Blackberry' Ice Popsicles: To prepare Indian blackberry ice popsicles, begin by thoroughly washing and deseeding fresh Indian blackberries. Next, weigh the berries and puree them using a blender. Strain the puree through a fine mesh sieve to achieve a smooth consistency, effectively removing any pulp and seeds. In a separate container, combine water and sugar, and bring this mixture to a boil. Once boiled, add the strained blackberry puree along with a blend of spices, including black salt, black pepper (*Piper nigrum*), and ginger powder (*Zingiber officinale*). This combination will create a flavourful spiced sugar syrup suitable for the popsicles. After the syrup has cooled to room temperature, incorporate spirulina powder (*Arthrospira platensis*), which adds nutritional benefits and color to the mixture. Pour the prepared mixture into stainless steel Popsicle moulds, ensuring they are filled appropriately to allow for expansion during freezing. Place the moulds in a freezer set at approximately -18 degrees Celsius to facilitate the freezing process. A stepwise flow chart has been included in Figure 1 to illustrate the Popsicle formulation and standardization process.

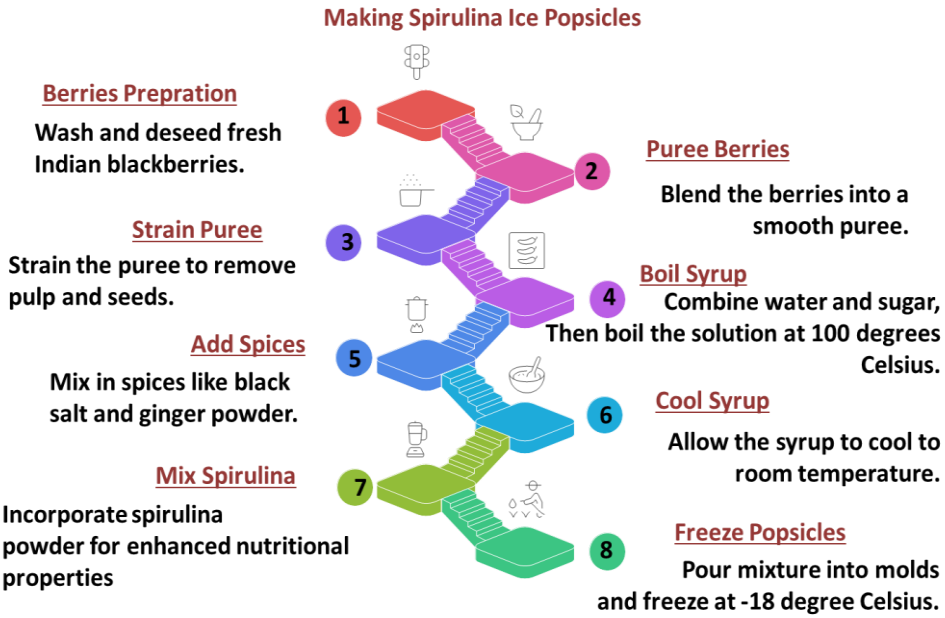


Figure 1: Popsicle formulation and standardization process

Yield Factor: The recipe yield was an essential step in recipe standardization. The main benefit of calculating yield was the avoidance of wastage of products by overproduction or underproduction. The yield factor is calculated based on the ratio of the weight of the uncooked raw materials before making the syrup and is expressed in serving size per popsicle. Yield factor = Edible Portion/Actual Portion*100 [19].

Table 2: Standardized Recipe for Indian Blackberry ice popsicle *Yield: 250 ml – 2-3 Popsicles / 100 ml each popsicle

Sr. No.	Ingredients	Amount (gm)
1	Sugar	20
2	Indian Blackberry Pulp (deseeded)	50
3	Spirulina	5
4	Ginger Powder	5
5	Black Salt	1.5
6	Black Pepper	5
7	Cumin Powder	5
8	Citric Acid	0.8
9	Water	158ml

Sensory Evaluation: A sensory evaluation was performed among trained panelists (n=5) to improve the product profile, while a 9-point hedonic scale was used to assess the acceptability of control and experimental ice popsicles on 20 semi-trained participants (18–45 years) with no known allergies to the test ingredients; samples were randomized in serving order to avoid bias.

Proximate Analysis: All proximate analyses were conducted in triplicate to ensure reproducibility using standard methods as per FSSAI guidelines [20], as presented in Table 3.

Table 3: Standard Methods as per FSSAI Manual:

Sr. No.	Parameters	Method Used
1	Moisture	Hot air oven drying
2	Total ash	Muffle furnace combustion
3	Fat	Soxhlet Extraction
4	Protein	Kjeldal method
5	Carbohydrate	IS:1656:2007 (RA 2012)
6	Energy	AFWTL/SOP/C-06
7	Total sugars	FSSAI Manual 2017
8	Beta carotene	HPLC method

Statistical Analysis: Data was analysed through the SPSS software version 20. Using paired comparison T-Test the hedonic rating scale scores and product profile scores were analysed for the control and experimental samples and p-values ≤ 0.05 were considered statistically significant.

Cost Estimation: The product's cost included both direct and indirect costs. The formulation cost encompasses the expenses for raw ingredients, as well as miscellaneous costs such as electricity, fuel, and packaging materials.

Packaging: The product was packaged in food-grade Zip-Lock bags made primarily from low-density polyethylene (LDPE) or polypropylene (PP), which are suitable for storing frozen food items. This sealable packaging prevents contamination, retains moisture, maintains the quality of the ice popsicle, and allows product visibility. A wooden stick was inserted into the popsicle mold for easy handling during consumption.

Processing of Indian Blackberry Seeds into Powder: After pulp extraction for popsicle development, the remaining Indian blackberry seeds were collected and

processed into powder using the following steps to ensure hygienic handling and nutrient preservation:

1. Collection and Cleaning: Seeds were manually separated from the pulp, thoroughly rinsed under running potable water to remove residual fruit matter, and drained using a muslin cloth.

2. Drying: Cleaned seeds were placed on stainless steel trays and shade-dried for 3 days to remove surface moisture. This was followed by oven drying at 50°C for 45 minutes until uniform drying was done. The drying temperature was chosen to preserve bioactive compounds while reducing microbial load.

3. Grinding and Sieving: The dried seeds were ground using a high-speed grinder to obtain a fine powder.

4. Storage: The blackberry seed powder was stored in an airtight container at ambient temperature in a dry, dark place to prevent oxidation or moisture uptake. The yield obtained from 20 grams of seeds as a dry powder was 4 grams. The seed powder was not added to the Popsicle in the final formulation but was retained as a functional by-product in line with the study's zero-waste approach. The powder was later analyzed for organoleptic properties and nutritional potential as part of future work on value-added product development.

Figure 2: L to R Deseeded Indian Blackberries (50g), Seeds (20g), Dried Seeds Powder (4g)

RESULTS

Recipe Yield: After standardization, the total yield in liquid form obtained was 250 ml. Each popsicle had a standardized serving size of 100 g, and approximately 2–3 popsicles were produced from 250 mL of the formulated liquid.

Figure 3: Final popsicle

Figure 4: Illustrative example of a proposed product label for the popsicle, developed solely for academic and research purposes. This label is intended to demonstrate nutritional declaration, ingredient listing, and front-of-pack communication for illustrative purposes and is not representative of an actual commercial product.

Sensory Evaluation: The average scores derived from the sensory evaluation are presented in Figure 5, depicted as a bar graph. The x-axis corresponds to the average scores obtained from the sensory assessment, while the y-axis represents the various sensory attributes evaluated. The overall acceptability scores for the experimental ice popsicles surpassed 80%, indicating a high degree of consumer acceptance. A statistical comparison was conducted using a paired t-test, which revealed a significant difference between the control and experimental products ($p \leq 0.05$). The experimental popsicle was found to be 34.31% more acceptable than the control popsicle.

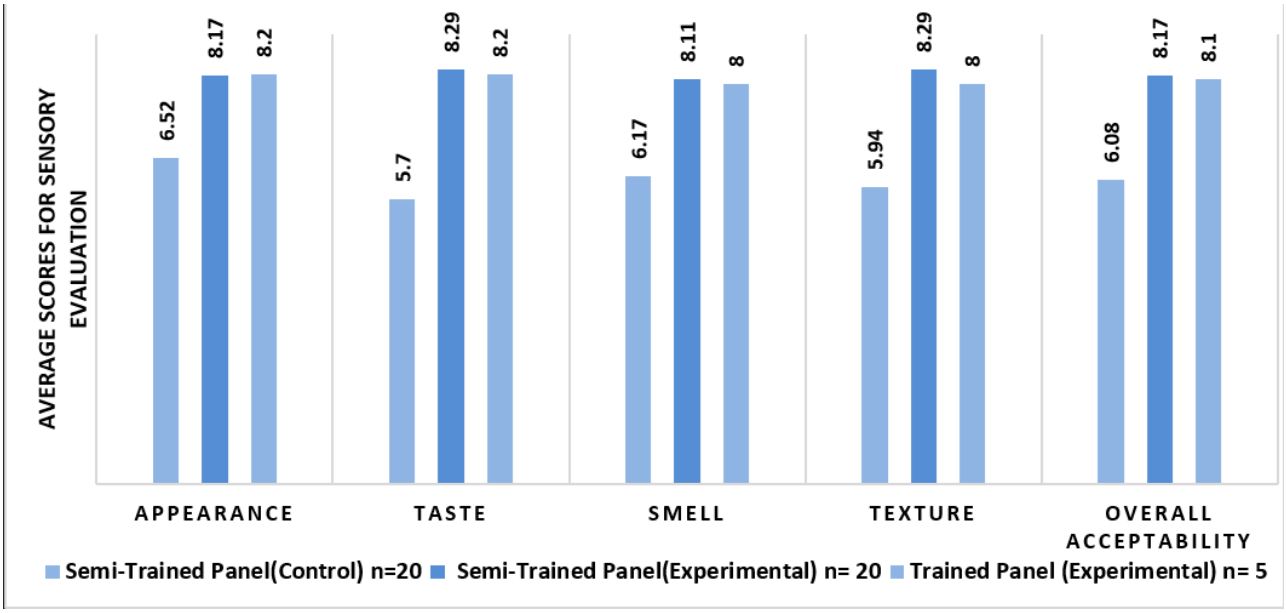


Figure 5: Sensory evaluation mean scores for appearance, taste, smell, texture, and overall acceptability of spirulina-enriched popsicle (experimental) and control, assessed using a 9-point hedonic scale by semi-trained (n = 20) and trained panelists (n = 5). Differences between the control and experimental samples were statistically significant for all attributes ($p \leq 0.05$) using a paired t-test.

Nutritive Value Estimation: Table 3 shows the nutritive value and % daily value comparison between control and experimental ice Popsicle per 100 grams of the product. The total moisture content of the experimental ice pop was 53g, and the ash content was 3g. The experimental spirulina-enriched Indian blackberry ice popsicles were found to be high in Vitamin A, high in protein, low in total fat, and low in total sugars. The daily percentage (%) values were based on a 2000-kilocalorie diet. The developed spirulina ice popsicles contributed 3.6% of daily values for calories. 2.12 % for proteins, 13.12% for carbohydrates, 0.88% for fats, and 27.83% for vitamin A.

Table 3: Nutritive value and percentage daily value per popsicle for the control (commercially available) and experimental (Indian blackberry and spirulina-enriched) formulations. *Daily Value per 2000 K Calorie diet

S. No.	Nutrients	Control	% DV	Experimental	% DV
1	Energy (in kcal)	85	4.15	72.02	3.6
2	Carbohydrates (in grams)	21	9.45	13.12	4.77
3	Protein (in grams)	0	0	2.12	4.24
4	Total Sugars (in grams)	21	42	9.54	19.08
5	Total fat (in grams)	0	0	0.88	1.12
6	Vitamin A (in µg)	0	0	15.11	27.83
7	Iron (in mg)	0	0	5.01	4.77
8	Vitamin C (in mg)	0	0	4.3	8.99
9	Magnesium (in mg)	0	0	37.79	21.51
10	Sodium (in mg)	15	0.65	259.12	11.26

Cost Estimation: The Cost of one spirulina popsicle formulation was INR 5, based on local wholesale market prices for the quantities used in preparation. The total cost incurred for making the product with packaging and fuel cost was found to be INR10. The selling price was finalized as INR 30.

Microbial Assessment: The spirulina–blackberry popsicle was examined for microbiological quality following FSSAI (2011; Appendix B, Part II) standards for frozen desserts [21]. Tests included Standard Plate Count (SPC), coliforms, yeast and mold, and *Escherichia coli*. Throughout the storage period, microbial loads stayed well within permissible limits, and no coliforms or pathogenic *E. coli* were found. These results confirmed that the product remained microbiologically safe when stored at –18 °C.

Sensory Shelf-Life Evaluation: Sensory quality was monitored using a 9-point hedonic scale. Although the product maintained microbiological safety during storage, consumer acceptability declined after Day 5,

particularly in texture and flavor. Based on sensory acceptability, the spirulina–blackberry popsicle was assigned a best-before date of 5 days for frozen storage.

DISCUSSION

The findings of this work highlight a significant innovation in functional food science. This frozen, plant-based confection integrates a protein-rich microalga (Arthrospira platensis) with an indigenous fruit (Syzygium cumini), resulting in a product that is both nutritionally superior and highly palatable. The 55% reduction in sugar content without sensory compromise, coupled with the use of fruit seed waste for functional powder production, underscores a holistic approach to product design that combines nutrition, sensory appeal, and sustainability —a combination less reported previously in the frozen dessert category. This innovation builds on the well-established functional potential of spirulina, which, beyond its role as a dietary supplement, has emerged as a rich source of single-cell proteins, potent antioxidants, and bioactive compounds with cardiovascular and neuroprotective benefits**.** Recent consumer studies have focused on organoleptic evaluations of spirulina fortification and enrichment in day-to-day routine foods. The present study used Indian blackberry as a base juice for enrichment of spirulina. The intake of processed beverages and foods substantially increases the sugar intake among individuals. Such added sugars, in the form of sugar syrups, which are incorporated into beverages and frozen ice candies to enhance taste, acceptability, and shelf life during food and industrial preparation, have been identified as a major contributor to obesity and dental caries [22-24]. The empty calories provided by such products have prompted demand for healthy alternatives using functional ingredients that are not only nutrient-dense but also low in sugars, fats, and calories, yet with reasonable amounts of protein and micronutrients, among food product development researchers.

Emerging evidence suggests that functional foods can play a crucial role in modulating the gut–immune–metabolic axis, which is increasingly recognized as central to chronic disease prevention and management. Dysbiosis, characterized by disrupted gut microbial composition, is closely linked to increased intestinal permeability, systemic inflammation, and insulin resistance, which together drive metabolic dysregulation. Interventions such as prebiotics, probiotics, and synbiotics have shown promise in improving metabolic control in such settings by restoring microbial balance and reducing inflammation [25]

In this context, functional ingredients such as Arthrospira platensis (spirulina) take on added significance. Spirulina's antioxidant and anti-inflammatory properties, combined with its potential to modulate the gut microbiota, may complement such interventions and enhance metabolic resilience. The incorporation of spirulina into a nutrient-dense, low-sugar frozen confection not only offers immediate dietary benefits but may also hold long-term implications for metabolic health, particularly in populations vulnerable to diet–microbiome–disease interactions.[26]

The present study adds to the body of research on food product development that incorporates spirulina into edible ice, such as ice lollies or ice popsicles. The formulated Spirulina-enriched blackberry popsicle falls under the edible ices category 3.0.2 of frozen desserts and frozen confections, as per the FSSAI Food Category System (FCS) and the Food Safety & Standards (Food Products Standards & Food Additives) Regulations, 2011 [27]. Usually, popsicles are empty calories, rich in sugars, edible ice usually containing artificial colors and preservatives; however, it is a popular food item across all age groups [28]. The selection of ice popsicles as the product matrix was based on their wide popularity and acceptability across all strata of society. Indian

blackberry (*Syzygium cumini*), commonly known as "Jamun" in Hindi, was chosen as the base juice for spirulina fortification owing to its rich phytonutrient profile [16]. Evidence suggests that Indian blackberry exhibits potential health benefits in the prevention and management of neurological disorders, diabetes, cancer, and cardiovascular diseases [29]. Furthermore, prior food product development studies have successfully utilized ice popsicles as a base for incorporating vegetables and herbs into functional ice lollies [30].

The finalization of the recipe of Indian blackberry spirulina popsicles was completed by various recipe trials till the product achieved standardization. The formal and informal trials helped conclude the final recipe and product, which was most accepted. The 9-point hedonic scale was used to understand the product's preference and overall acceptability. It was suggested that the product needs improvement in texture compared to contemporary popsicles. The product scored highest for its vibrant color and lingering aftertaste.

A similar ice pop with Indian blackberry has a base ingredient that uses whey in the Indian blackberry ice pops as a diabetic friendly food product [31]. Our findings support the growing body of evidence showing that bioactive compounds and functional foods can influence health outcomes beyond traditional nutrient delivery.

Bioactive compounds (BCs) are central to the formulation and functionality of modern functional foods (FFs), as they contribute significantly to health benefits beyond basic nutrition. These compounds, including polyphenols, antioxidants, dietary fibers, carotenoids, fatty acids, prebiotics, and probiotics, are widely recognized for their roles in preventing and managing chronic diseases, improving metabolic health, and enhancing overall well-being. As defined by the Functional Food Center (FFC), BCs are "constituents of foods" that exert beneficial physiological effects, and their efficacy is closely linked to their dosage, interaction within the food matrix, and long-term safety profile [32]. Many of these bioactives occur naturally in fruits, vegetables, and whole grains. A study on rice-derived glucosylceramides demonstrated enhanced activation of antigen-presenting cells and improved resistance to common cold symptoms [33]

In a similar vein, spirulina, known for its antioxidant, anti-inflammatory, and immune-modulating properties, may offer complementary benefits when incorporated into a frozen fruit-based matrix, extending the scope of functional food innovation and its integration into functional food formulations, such as how the spirulina–Syzygium cumini popsicle enhances the product's nutritional and therapeutic potential.

Spirulina (Arthrospira platensis) is a nutrient-dense microalga that contains a broad spectrum of bioactive compounds responsible for its significant functional and therapeutic potential. Among the most notable are phycobiliproteins, particularly phycocyanin, which exhibit potent antioxidant, anti-inflammatory, and immunomodulatory properties. Spirulina is also rich in carotenoids such as β-carotene, lutein, and zeaxanthin, which support vision and immune function. In contrast, essential fatty acids, such as γ-linolenic acid (GLA), contribute to cardiovascular and metabolic health. Moreover, the presence of polysaccharides, phenolic compounds, and sulfated glycolipids further enhances its ability to modulate immune responses and protect against oxidative stress. Minerals (iron, magnesium, zinc) and vitamins (notably vitamin B12 and provitamin A) complement these bioactives, making spirulina a multifunctional ingredient that can influence gut health, metabolic regulation, and chronic disease prevention. Collectively, these bioactive components underscore spirulina's potential as a versatile functional food ingredient with applications ranging from immune modulation to metabolic health support [34].

Likewise, the other functional ingredient used in popsicle development was Indian blackberry (Syzygium cumini), rich in bioactive compounds such as phenolic acids (gallic, ellagic), flavonoids (quercetin, myricetin, kaempferol), tannins, and anthocyanins (delphinidin, petunidin, malvidin), which provide potent antioxidant, anti-inflammatory, and chemopreventive effects. Additionally, alkaloids such as jambosine and glycosides such as jambolin exhibit anti-diabetic activity. Together, these phytochemicals support cardiovascular health, regulate blood glucose, and enhance the functional value of food products [35]. Recent evidence supports the growing role of plant-derived bioactives in disease prevention and metabolic health. For example, the *Moringa oleifera* leaf extract shows potent antioxidant and hepatoprotective effects, reducing liver damage and improving antioxidant enzyme activity [36]. At the same time, a multi-ingredient dietary formulation significantly lowered blood glucose and improved glucose tolerance in hyperglycemic models [37]. These findings reinforce the potential of bioactive-rich functional foods, such as the spirulina–Syzygium cumini used in the popsicle, to offer additional metabolic and organ-protective benefits.

Another unique feature of the product was its natural ingredients; no chemical preservatives, artificial ingredients, or additives were used, making it a clean-label ice popsicle [38]. The shelf-life of the spirulin-enriched Indian blackberry popsicle was limited to 5 days due to sensory quality changes observed during frozen storage, primarily because it lacked synthetic preservatives. In keeping with the product's clean-label objective, no chemical stabilizers or antimicrobial agents were incorporated into the formulation; only citric acid, a naturally occurring acidulant, was included to maintain pH and support minimal microbial control. In contrast, commercially available frozen desserts often employ preservatives such as sodium benzoate, potassium sorbate, or sulfites to extend shelf-life and inhibit microbial growth. The deliberate exclusion of such additives in this study prioritized ingredient transparency and consumer safety, even at the expense of shorter storage stability. Future work could explore natural preservation strategies such as plant-derived antioxidants, fermentation-based bio-preservatives, or hurdle technology to enhance shelf-life while retaining a clean-label profile.

It was also observed that the spirulina ice popsicle was a potential nutrient-dense product, containing a good amount of minerals and Vitamin A (15.11 µg), which is higher than in any fruit ice or popsicle.

This product has scope for inclusion in government midday meals for children during all seasons, especially in summer, as ice lollies or ice candy, which children love. This product, with its high nutrient density and spirulina benefits, would serve as a feasible way to tackle micronutrient malnutrition in a tasty way. Considering its health benefits, it is a nutrient-dense frozen item enjoyed by all age groups. More such food products incorporating spirulina should be developed, analyzed, and supplemented. Spirulina-enriched food products serve as healthy alternatives to commercially available products, making them a potent superfood for incorporation into daily diets.

Strengths and Limitations: Spirulina ice popsicle is a new addition to the range of spirulina-enriched products, developed through this product development and sensory acceptability assessment research. The product supports clean-label foods as it includes only natural preservatives, such as sugar, and does not use any artificial colors. It has the natural colors of blackberries. The product is a good source of micronutrients and antioxidants provided by spirulina and Indian blackberry juice. Consuming 1 Popsicle delivers 1.6 g of spirulina, which roughly meets the micronutrient density of ½ to 1 portion of fruits/vegetables, especially for vitamin A, iron, and antioxidant phytonutrients. The study has developed a

product based on an indigenous fruit and superfoods, with no preservatives, artificial sweeteners, or colors, and it has the potential for good commercial acceptability. While this study recognized a short-term 'best before' period, extended shelf-life calculation, including the use of natural stabilizers or alternative natural preservative strategies, will be vital before marketable scale-up.

While the spirulina-enriched blackberry popsicle demonstrated acceptable microbiological quality and safety throughout storage and maintained sensory acceptability up to 5 days under frozen conditions, this study did not evaluate the detailed shelf-life stability beyond sensory parameters. Micronutrient retention, bioavailability, and potential degradation of bioactive compounds during processing and storage were not assessed, which limits understanding of the product's long-term nutritional efficacy. Future studies should include comprehensive analyses of nutrient stability and bioavailability to strengthen the product's functional food claims.

Scientific Innovation and Practical Implications: This study advances existing knowledge by demonstrating the successful formulation of a spirulina-enriched frozen dessert using Indian blackberry as a culturally familiar base. While spirulina has been widely studied as a dietary and nutraceutical supplement, its use in frozen, ready-to-consume formats has been limited, particularly when paired with indigenous fruits. By linking sensory acceptability, nutritional profiling, and market feasibility, this work shows that functional food innovation can move beyond capsules and powders to become part of everyday foods that are both enjoyable and health-promoting.

From a practical perspective, the spirulina popsicle developed here provides a low-sugar, nutrient-rich alternative to commercially available frozen desserts, addressing the dual challenge of hidden sugars and widespread micronutrient deficiencies. The product offers potential application in school feeding programs, quick-service retail, and the growing clean-label frozen foods market. Its alignment with zero-waste practices through seed valorisation adds further value, making it relevant not only for nutrition security but also for sustainable food entrepreneurship.

This study offers a replicable model for enriching microalgae and indigenous fruits into traditionally acceptable food product formats, opening the way for research on shelf-life stability, large-scale processing, and consumer acceptance across varied populations. By uniting nutritional science, sensory evaluation, and sustainability, the effort reinforces the evidence base for functional foods that are both scientifically reliable and socially relevant.

CONCLUSION

The present study exhibits the formulation of a spirulina-enriched Indian blackberry popsicle that syndicates high nutrient density, consumer acceptability, and alignment with clean-label and zero-waste principles. By coupling spirulina, a globally recognized microalgae superfood, with an indigenous, anthocyanin-rich, local seasonal fruit such as Indian blackberry, this work provides evidence of synergistic functional food innovation within a culturally familiar frozen dessert matrix. The product showed higher sensory scores, lower sugar content, and higher levels of protein, vitamin A, and iron than conventional popsicles. Prominently, the valorisation of Indian blackberry seed waste demonstrates a circular food systems approach that boosts sustainability.

Beyond its technical and sensory attributes, the spirulina–blackberry popsicle holds translational relevance for addressing micronutrient deficiencies, childhood malnutrition, and excess sugar intake, which are pressing public health concerns in India and globally. Its feasibility as a school-friendly frozen snack or community-level functional food intervention positions it as a practical tool to improve nutritional

security while satisfying consumer demand for palatable, convenient foods. Future research should focus on extended shelf-life optimization, bioavailability studies of spirulina-derived bioactive compounds in frozen matrices, and bigger consumer trials across age groups and geographies to establish generalizability. Collectively, this work advances the field of functional foods by offering a replicable model for incorporating microalgae into affordable, widely acceptable, and sustainable food innovations that bridge the gap between laboratory development and market-ready solutions.

List of Abbreviations: CAGR- Compound annual growth rate, FAO- Food and agriculture organization, GLA- Gamma Linolenic Acid, WHO- World Health Organization, USFDA United States Food and drug administration, GRAS- Generally recognized as safe, RDA- Recommended dietary allowance, IFCT- Indian food composition table, LDPE- Low-density polyethylene, PP- Polypropylene, INR- Indian rupees, g- grams, Kcal- kilocalories, mg- Micrograms, SPC- Standard plate count, FSSAI- Food safety and standard authority of India, FCS- Food category system.

Acknowledgments and Funding: The authors acknowledge the use of Napkin AI and Canva platforms, which facilitated the design and visualization of the graphical abstract. No financial assistance was received for conducting this study.

Competing Interests: The Authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions: RH conceptualized and standardized the research protocol and food product development protocol. RH, SC, and AS performed the practical experiments and data analysis. RH and AS wrote the manuscript, and RH and MP reviewed the manuscript and provided edits as required. All authors read and approved the final manuscript.

REFERENCES:

1. Grand View Research. India vegan popsicles market size, share & trends analysis report. 2024. Available from: https://www.grandviewresearch.com/industry-analysis/vegan-popsicles-market-report
2. Business Research Insights. (2024). Global popsicle market size, share, and growth analysis report, 2024–2031.Available from: https://www.businessresearchinsights.com/market-reports/popsicle-market-120398
3. Fekete M, Lehoczki A, Kryczyk-Poprawa A, Zábó V, Varga JT, Bálint M, et al. Functional Foods in Modern Nutrition Science: Mechanisms, Evidence, and Public Health Implications. Nutrients. 2025 Jun 28; 17(13):2153. DOI: https://doi.org/10.3390/nu17132153
4. Saras T. Spirulina Uncovered: Exploring the Green Superfood's Nutritional Marvels and Health Benefits. Tiram Media; 2023 Aug 17.
5. Verma AK, Dewangan K, Daunday L, Naurange K, Verma K, Bhiaram M. Spirulina as functional food: insights into cultivation, production, and health benefits. Journal of Applied Pharmaceutical Research. 2024 Oct 31; 12(5):28-50. DOI: https://doi.org/10.69857/joapr.v12i5.788
6. Marjanović B, Benković M, Jurina T, Sokač Cvetnić T, Valinger D, Gajdoš Kljusurić J, et al. Bioactive compounds from Spirulina spp.—Nutritional value, extraction, and application in food industry. Separations. 2024 Aug 30; 11(9):257. DOI: https://doi.org/10.3390/separations11090257
7. Food and Agriculture Organization of the United Nations (FAO). The global status of commercialized microalgae: Opportunities and challenges. Rome: FAO; 2021.Available from:https://openknowledge.fao.org/server/api/core/bitstreams/43da43ad-be75-4aaa-ba4a-e375b1c65cfc/content
8. Podgórska-Kryszczuk I. (2024). Spirulina-An Invaluable Source of Macro- and Micronutrients with Broad Biological Activity and Application Potential. Molecules (Basel, Switzerland), 29(22), 5387. DOI: https://doi.org/10.3390/molecules29225387
9. Yalçın B., Beştepe S.K., Akyılmaz M.K. Investigation of the use of microalgae in ice cream formulation. ITU J Food Sci Technol. 2024; 2(2):47–56.
10. Babashpour-Asl M, Eghlima G. Detection of proximate, phytochemical compositions, phycocyanin and

antioxidant activity of Arthrospira platensis (Spirulina). Applied Phycology. 2025 Dec 31;6(1):178-89.
DOI: https://doi.org/10.1080/26388081.2025.2509847

11. Guan F, Fu G, Ma Y, Zhou L, Li G, Sun C, et al. Spirulina polysaccharide-based prebiotic foods preparations-a promising approach for modulating gut microbiota and improving health. Journal of Functional Foods. 2024 May 1; 116:106158.
DOI: https://doi.org/10.1016/j.jff.2024.106158
12. Koli, D. K., Rudra, S. G., Bhowmik, A., & Pabbi, S. (2022). Nutritional, Functional, Textural and Sensory Evaluation of Spirulina Enriched Green Pasta: A Potential Dietary and Health Supplement. Foods (Basel, Switzerland), 11(7), 979.
DOI: https://doi.org/10.3390/foods11070979
13. Kumar V, Khatri N, Kumar D, Shekhawat M, Vandana Garg V, Kumar A, et al. Modern perspectives on the traditional uses, phytochemical profiles, and therapeutic benefits of Syzygium cumini. Integr Med Discov. 2025; 9:e25007.
DOI: https://doi.org/10.53388/IMD202509007
14. Pal I., Bose C. Spirulina—a marine miracle for sustainable food system. Mar Biol Res. 2022; 18(1):1–17.
DOI: https://doi.org/10.1080/17451000.2022.2101122
15. Gil-Martínez L, Mut-Salud N, Ruiz-García JA, Falcón-Piñeiro A, Maijó-Ferré M, Baños A, et al. Phytochemicals determination, and antioxidant, antimicrobial, anti-inflammatory and anticancer activities of blackberry fruits. Foods. 2023 Apr 3; 12(7):1505.
DOI: https://doi.org/10.3390/foods12071505
16. Singh H, Sharma V, Sharma B, Kumar M, Rana N. Jamun (Syzygiumcumini L.) Seeds: A Review on Phytochemistry, Pharmacology, Nutritional Profile and traditional uses.
17. Longvah T., Ananthan R., Bhaskarachary K., Venkaiah K. Indian food composition tables 2017. Hyderabad: National Institute of Nutrition, ICMR; 2017.Available from: https://www.nin.res.in/ebooks/IFCT2017.pdf
18. U.S. Department of Agriculture. Recipe standardization guide for the child and adult care food program. University, MS: Institute of Child Nutrition, University of Mississippi; 2024.
19. Tian X, Engel BA, Qian H, Hua E, Sun S, Wang Y. Will reaching the maximum achievable yield potential meet future global food demand?. Journal of Cleaner Production. 2021 Apr 20; 294:126285.
DOI: https://doi.org/10.1016/j.jclepro.2021.126285
20. FSSAI. Manual of Methods of Analysis of Foods – Cereal and Cereal Products (2nd ed., 2022). Food Safety and Standards Authority of India. Available from: https://fssai.gov.in/upload/uploadfiles/files/Manual%20on%20Cereal%20and%20Cereal%20Products.pdf
21. Food Safety and Standards Authority of India (FSSAI). Food Safety and Standards (Food Products Standards and Food Additives) Regulations. Appendix B, Part II: Standards for Frozen Desserts. New Delhi: Government of India; 2011.
22. Ramos SD, Bürck M, Costa SF, Assis M, Braga AR. Spirulina as a Key Ingredient in the Evolution of Eco-Friendly Cosmetics. BioTech. 2025 May 30;14(2):41.
DOI: https://doi.org/10.3390/biotech14020041
23. Saeed F, Tul-Zohra K, Naveed K, Zia A, Khaliq M, Noor Z, et al. Algal Proteins for Sustainable Nutrition and Functional Food Innovation. Applied Food Research. 2025 Feb 25:100752.
DOI: https://doi.org/10.1016/j.afres.2025.100752
24. Sahil S, Bodh S, Verma P. Spirulina platensis: a comprehensive review of its nutritional value, antioxidant activity and functional food potential. Journal of Cellular Biotechnology. 2024 Nov 25; 10(2):159-72.
DOI: https://doi.org/10.3233/JCB-240151
25. Rithi AT, Mitra A, Banerjee A, Ilanchoorian D, Marotta F, Radhakrishnan AK. Effect of prebiotics, probiotics, and synbiotics on gut microbiome in diabetes among coastal communities. Funct Food Sci. 2024 Jan 8;4(1):11–28.
DOI: https://doi.org/10.31989/ffs.v4i1.1271
26. AlFadhly NKZ, Alhelfi N, Altemimi AB, Verma DK, Cacciola F, Narayanankutty A. Trends and technological advancements in the possible food applications of Spirulina and their health benefits: A review. Molecules. 2022; 27(17):5584.:
DOI: https://doi.org/10.3390/molecules27175584
27. Food Safety and Standards Authority of India (FSSAI). Food Safety and Standards (Food Products Standards and Food Additives) Regulations, 2011. Food Category System (FCS): Frozen desserts and frozen confections, Category 3.0.2. New Delhi: Government of India; 2011.
28. Krick HM. Functional popsicles: A sensory evaluation and product optimization study [dissertation]. Philadelphia, PA: Drexel University; 2023.
DOI: https://doi.org/10.17918/00002002
29. Buczyński K, Kapłan M, Jarosz Z. Review of the report on the nutritional and Health-Promoting values of species of the rubus L. Genus. Agriculture. 2024 Aug 9; 14(8):1324.
DOI: https://doi.org/10.3390/agriculture14081324
30. Tsegay ZT, Gebreegziabher ST, Mulaw G. Nutritional qualities and valorization trends of vegetable and fruit byproducts: a comprehensive review. Journal of Food Quality. 2024; 2024(1):5518577.

DOI: https://doi.org/10.1155/2024/5518577

31. Jan Y., Malik M., Sharma V., Yaseen M., Bora J., Haq A. Utilization of whey for formulation of whey jamun juice ice pops with antidiabetic potential. Food Front. 2021; 2(4):486–493. DOI: https://doi.org/10.1002/fft2.90
32. Martirosyan D. Functional food science and bioactive compounds. Bioact Compd Health Dis. 2025 Jun 30;8(6):218–29.
DOI: https://doi.org/10.31989/bchd.v8i6.1667
33. Miyasaka K, Takeda S, Yoneda A, Kubo M, Shimoda H. Rice-derived glucosylceramides up-regulate HLA-DR expression on myeloid dendritic cells to activate innate immune responses in healthy Japanese subjects: a randomized, placebo-controlled, double-blind trial. Funct Food Sci. 2025 Aug 4;15(8):506–18.
DOI: https://doi.org/10.31989/ffhd.v15i8.1666
34. Bortolini DG, Maciel GM, Fernandes ID, Pedro AC, Rubio FT, Branco IG, Haminiuk CW. Functional properties of bioactive compounds from Spirulina spp.: Current status and future trends. Food Chem Mol Sci. 2022 Dec 30;5:100134
DOI: https://doi.org/10.1016/j.fochms.2022.100134
35. Das S, Samal SS, Jena A, Jena A, Chaitanya K, Kishan S, Dey S. Bioactive compounds in jamun (Syzygium cumini L.) ensuring nutritional security. In: Futuristic Trends in Agriculture Engineering & Food Sciences. IIP Series. 2024; 3:186–194.
36. Xie B, Chen P, Hong Y, Xu C, Zhang W. Effects of a dietary compound tablet on glucose metabolism in a hyperglycemic mouse model. Dietary Suppl Nutraceuticals. 2025 Jun 6; 4(6):1–1.
DOI: https://doi.org/10.31989/dsn.v4i6.1621
37. Zakari AD, Audu GA, Egbeja TI, Aliyu AA, Adefila MA, Momoh TB, et al. Antioxidant and hepatoprotective activities of methanol extract of Moringa oleifera leaves in carbon tetrachloride-induced hepatotoxicity in rats: implications for functional food development. Agric Food Bioact Compd. 2025;2(7):157–68.
DOI: https://doi.org/10.31989/afbc.v2i7.1722
38. Chauhan K, Rao A. Clean-label alternatives for food preservation: An emerging trend. Heliyon. 2024 Aug 30;10(16).
DOI: https://doi.org/10.1016/j.heliyon.2024.e35815