International Journal of Gastronomy Research

Lactic-Acid-Fermented *Chlorella vulgaris* as a Novel Ingredient for Gummy Candies: Physicochemical, Textural, and Sensory Characteristics

Serpil Pekdoğan Göztok[1] and Cihat Güner[2,*]

[1] *Siirt University, Department of Food Technology, Vocational School of Technical Sciences, 56000, Siirt, Türkiye*
[2] *Karakuru Research and Development Center, 34220, İstanbul, Türkiye*

Abstract

There is increasing interest in plant-based ingredients that can contribute both visual appeal and distinctive sensory characteristics to food products. In this context, lactic-acid-fermented microalgae represent a promising alternative due to their natural pigmentation and potential to influence sensory and structural properties. This study investigated the use of lactic-acid–fermented *Chlorella vulgaris* as a novel ingredient in gummy candies, with the aim of evaluating its effects on color, texture, and overall eating quality within a familiar confectionery matrix. Fermented microalgal biomass was incorporated into a standard gelatin–sugar gummy formulation at levels of 3%, 6%, and 9% (w/w), and the resulting samples were characterized in terms of physicochemical properties, color (*CIE L*a*b**), texture profile, and sensory attributes. The addition of fermented Chlorella slightly modified pH and density while maintaining a high soluble-solid content, thereby preserving the characteristic chewy structure of gummy candies. At 3% inclusion, samples exhibited a brighter appearance with a blue-green hue and increased chroma, whereas higher concentrations resulted in darker and more opaque gels with deeper green coloration. Texture analysis indicated that hardness and gumminess remained within acceptable ranges, while cohesiveness and resilience showed a gradual shift toward a more energy-absorbing gel structure as algae concentration increased. Sensory evaluation demonstrated that formulations containing 3% and 6% fermented Chlorella achieved overall acceptability comparable to the control, whereas the 9% formulation showed more pronounced color and flavor characteristics, accompanied by a moderate decrease in overall acceptability. Overall, these findings suggest that lactic-acid-fermented *Chlorella vulgaris* may be considered as a techno-functional ingredient in confectionery formulations, particularly in terms of color contribution and textural modulation. However, its potential applications in gastronomy or culinary design should be interpreted cautiously and require further validation using professional culinary evaluation and broader consumer studies.

Keywords: *Chlorella vulgaris*, Fermented microalgae, Gummy candies, Sensory evaluation, Texture profile analysis.

Research Article / *Received:* 28 November *2025*, *Accepted: 31 May 2026*, *Published Online:* 11 June *2026*.

1. Introduction

The global interest in functional foods has increased substantially in recent years, with a particular emphasis on incorporating health-promoting ingredients into confectionery and gastronomic products to meet evolving consumer expectations (Bigliardi & Galati, 2013; Granato et al., 2010). Traditional gummy candies and similar soft confectioneries have been criticized for their high sugar content, low nutritional value, and limited functional properties (Mutlu et al., 2018). Despite these limitations, the gummy sector has emerged as a significant platform for gastronomic innovation by shifting toward new formulations enriched with natural ingredients, plant extracts, and functional additives (Pekdoğan Göztok et al., 2024; Roudbari et al., 2024). Consequently, the incorporation of functional food components into gummy matrices has become an expanding research domain for both industry and academia.

In recent years, microalgae have gained notable attention in the field of functional foods due to their rich content of proteins, pigments, vitamins, minerals, and various bioactive compounds (Batista et al., 2019; Becker, 2013). Among these, *Chlorella vulgaris* stands out owing to its protein content of up to 50%, abundant

* Corresponding Author: Cihat Güner
Email: drcihatguner@gmail.com
https://doi.org/10.56479/ijgr-72

chlorophyll and carotenoid pigments, essential amino acids, and strong antioxidant capacity (Lafarga & Acién, 2022). The sustainable production, high biomass yield, and low environmental footprint of microalgae make them valuable resources for clean-label and health-oriented product development (Bleakley & Hayes, 2017).

The direct incorporation of microalgae into food matrices may lead to several sensory limitations; in particular, the characteristic green color, herbaceous–alkaline taste profile, and vegetal aroma of Chlorella species can restrict the overall sensory acceptability of the final product. These sensory challenges are primarily attributed to the presence of chlorophyll and its derivatives, lipid oxidation products, and aldehydes responsible for "green" aroma notes within the microalgal biomass (Matos, 2022; Çelekli et al., 2024). Therefore, processing strategies aimed at improving the taste–flavor profile of microalgae and mitigating their characteristic "algal" off-flavor have become a critical step in functional food applications (Nicolotti et al., 2025).

In this context, lactic acid fermentation has recently emerged as an effective approach for enhancing both the sensory and functional properties of microalgae. Furthermore, fermentation contributes to improved color stability through the partial degradation of chlorophyll and has been noted to enhance digestibility, as documented in recent literature (Sarıtaş et al., 2024).

Most studies on functional gummies have focused on the use of natural antioxidants, fruit extracts, natural colorants, and probiotic components. For instance, Roudbari et al. (2024) developed functional gummies using stevia and natural phenolic extracts; Gorjanović et al. (2024) reported that enriching pectin-based fruit jellies with polyphenols significantly enhanced their antioxidant capacity and functional properties; and Gorjanović et al. (2024) evaluated the phenolic profiles of gummy products enriched with vegetable pomace. Mutlu et al. (2018) formulated sugar-free gummies using honey, while Caleja et al. (2015) demonstrated that natural plant extracts can provide functional benefits within food matrices. However, no study in the current literature has examined the incorporation of fermented microalgae into gummy formulations or evaluated its effects on quality parameters, texture, and sensory attributes. Although Akelom et al. (2022) optimized the nutritional and sensory characteristics of gummy products developed with cactus fruit and *Moringa oleifera* extract, they did not employ microalgal ingredients. Therefore, the development of gummies containing fermented Chlorella vulgaris appears to represent a novel approach in this research area.

Quality parameters in gummy products are generally evaluated through color (L^*, a^*, b^*) and gloss measurements, textural properties (hardness, elasticity, chewiness), pH, °Brix, moisture/solids content, and sensory acceptability (Bourne, 2002; León et al., 2006; Pathare et al., 2013). The role of hydrocolloids in gel network formation and texture stability is well established, and the distribution and water interactions of functional ingredients within this matrix substantially influence both textural and sensory quality (Wüstenberg, 2014). Numerous studies highlight that formulations containing natural pigments, fiber fractions, or microalgae may exhibit alterations in elasticity, hardness, opacity, and chewiness, while color and aroma remain critical determinants of consumer acceptance (Gorjanović et al., 2024).

This study investigated the incorporation of lactic acid–fermented *Chlorella vulgaris* into gummy formulations at levels of 3%, 6%, and 9%, and evaluated its effects on physicochemical properties, color, texture, and sensory characteristics. The findings provide insight into the potential use of fermented microalgae as a novel techno-functional ingredient in value-added confectionery products for the functional food and gastronomy sectors.

2. Materials and Methods

2.1. Materials

Chlorella vulgaris used in this study was supplied in its lactic-acid–fermented form by Kybele's Garden (Ankara, Türkiye). The fermentation process was carried out by the supplier using a proprietary and patented method registered by the Turkish Patent and Trademark Office (Patent No: 2024/012266), and detailed fermentation conditions were not disclosed due to commercial confidentiality. According to the manufacturer's product information, the fermented microalgal biomass had an approximate dry matter content of 10% and contained approximately 5-6% protein. In addition, the product was reported to contain naturally occurring pigments and characteristic microalgal components associated with *Chlorella vulgaris*. These compositional values were based on supplier-provided information and were not independently verified within the scope of the present study. The fermented algal biomass was incorporated into gummy formulations at different concentrations as described below.

Food-grade sucrose, glucose syrup, bovine gelatin (250 Bloom), and citric acid monohydrate used in gummy production were obtained from local food ingredient suppliers. Silicone molds used for gummy shaping were purchased from local food-grade material suppliers. Reagents and analytical chemicals used for physicochemical analyses, including sodium chloride, ethanol, buffer solutions, and other analytical-grade chemicals, were purchased from Sigma-Aldrich (St. Louis, MO, USA). All solutions were prepared using distilled water, and all chemicals were of analytical grade unless otherwise specified.

2.2. Formulation development rationale

The selection of fermented *Chlorella vulgaris* biomass incorporation levels (3%, 6%, and 9%, w/w) was based on preliminary formulation trials and practical considerations regarding product quality and process feasibility. In initial screening trials, concentrations below 3% resulted in minimal observable changes in physicochemical and sensory properties, whereas levels above 9% led to undesirable textural softening and intensified off-flavor development, negatively affecting overall acceptability. Therefore, incorporation levels between 3% and 9% were selected as a practical working range for evaluating the effects of fermented algae in gummy formulations.

In the formulation design, fermented algae was incorporated by partially replacing the water fraction of the base recipe in order to maintain constant total batch weight and overall processing conditions. Consequently, increasing algae concentration was accompanied by a proportional reduction in added water content. Therefore, the formulations differed not only in algae concentration but also in moisture composition.

As a result, the observed changes in physicochemical, textural, and sensory properties may reflect both the direct effects of fermented algae incorporation and the indirect effects associated with reduced water content in the formulation. For example, variations in gel firmness, color intensity, and density may have been influenced simultaneously by algal components and changes in the water-to-solid ratio.

Although this formulation strategy reflects a realistic product development approach commonly used in confectionery applications, it limits the independent evaluation of algae concentration as a single experimental factor. Therefore, the results should be interpreted within the context of the combined formulation changes.

2.3. Gummy candy production

Gummy samples were produced according to the procedure of Pekdoğan Göztok et al. (2024) with several modifications to incorporate fermented algal biomass. A standard batch size of 500 g was used for all formulations. The control gummy formulation consisted of 7% gelatin, 40% sucrose, 35% glucose syrup and 18% water (w/w).

Sucrose, glucose syrup and water were transferred into a thermal mixer (Thermomix TM5, Vorwerk, Wuppertal, Germany) and heated to 105 °C under gentle agitation (200-300 rpm). Heating was continued until the soluble solids content reached approximately 82 °Brix, monitored with a hand refractometer (Hanna, H196801, USA), as described by Pekdoğan Göztok et al. (2024).

In a separate vessel, gelatin was pre-hydrated at a 1:3 (w/w) gelatin:water ratio. For each 500 g batch, 35 g of gelatin was dispersed in water preheated to approximately 60 °C and stirred until complete dissolution. When the concentrated syrup (82 °Brix) had cooled to 60 °C, the gelatin solution was incorporated into the syrup phase and the mixture was gently stirred for 5 min to obtain a homogeneous gel mass.

For the algae-enriched formulations, fermented algal biomass (10% dry matter) was incorporated by partially replacing the water fraction of the base recipe. The final compositions were 3% alg + 15% water, 6% alg + 12% water and 9% alg + 9% water (w/w), corresponding to 15, 30 and 45 g fermented alg per 500 g batch, respectively. During cooking, the fermented alg slurry was added when the syrup had reached approximately 78–82 °Brix; heating was then continued briefly to re-establish the target solids content while ensuring uniform distribution.

The hot gummy masses were poured into silicone molds and allowed to set at room temperature. After complete gelation, samples were demolded, packed in polyethylene bags and stored at 4 °C until analysis, following the general procedure of Pekdoğan Göztok et al. (2024).

2.4. pH, density, and °Brix content

The pH, density, and soluble solid content (°Brix) of the gummy samples were analyzed using standard procedures with slight modifications.

The pH values of the gummy samples were determined following the method described by Mutlu et al. (2018), with minor modifications. Approximately 10 g of homogenized gummy sample was dispersed in 100 mL of distilled water and allowed to equilibrate for 5 min under continuous stirring to ensure uniform dispersion. The pH was measured at room temperature using a calibrated digital pH meter (Metrohm pH-Meter E520, Herisau, Switzerland). All measurements were carried out in triplicate and results were expressed as mean ± standard deviation.

Sample density was measured according to Pekdoğan Göztok et al. (2024), using the mass-to-volume ratio method. Gummy cubes of known dimensions were prepared and their mass was recorded using a precision balance (±0.001 g). The displaced water volume in a graduated cylinder was used to calculate the density of each sample, expressed as grams per milliliter (g/mL), as shown in Equation (1).

$$\text{Density}\left(\frac{\text{g}}{\text{mL}}\right) = \frac{\text{Sample weight (g)}}{\text{Displaced volume (mL)}} \qquad \text{Eq.1}$$

Soluble solid content (°Brix) was determined according to the method described by Belitz et al. (2009), with slight modifications for gummy matrices. Approximately 2 g of homogenized gummy sample was dissolved in distilled water to obtain a uniform solution suitable for refractive index measurement. A few drops of the prepared sample solution were placed onto the prism surface of a digital refractometer, and measurements were performed at room temperature. Results were expressed as °Brix and reported as mean ± standard deviation of triplicate analyses.

2.5. Color measurement

The surface color characteristics of the gummy samples were evaluated using a colorimeter (Chroma Meter CR-400, Konica Minolta, Japan). Color parameters L^* (lightness), a^* (red–green axis), and b^* (yellow–blue axis) were recorded directly from the instrument. Measurements were performed on the surface of each gummy piece in triplicate.

In addition to the basic color coordinates, chroma (C*) and hue angle (h°) values were calculated to provide a more comprehensive description of color intensity and tonality, following the approach of Moghaddas Kia et al. (2020). Chroma and hue angle were computed using the Equations (2) and (3).

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \qquad \text{Eq.2}$$

$$h^{\circ} = \arctan\,(b^*/a^*) \qquad \text{Eq.3}$$

2.6. Texture profile analysis

The textural properties of the gummy samples were evaluated using a texture analyzer (XT Plus Texture Analyser, Stable Micro Systems, Godalming, UK) equipped with a P/35 cylindrical probe (35 mm diameter) and a 5 kg load cell. Prior to analysis, samples were equilibrated at room temperature (25 ± 2 °C) for 1 h, and cubic samples (approximately 10 × 10 × 10 mm) were used to ensure geometric consistency. Compression measurements were performed at a constant test speed of 1 mm/s (pre-test and post-test speeds were also set at 1 mm/s). Each sample was subjected to a two-cycle compression test to 50% of its original height, corresponding to approximately 5 mm deformation, with a 15-s interval between cycles to allow partial structural recovery. The force–time curves obtained from the instrument were used to calculate texture profile analysis (TPA) parameters according to standard methodology (Cano-Lamadrid et al., 2020).

Hardness was defined as the maximum force during the first compression cycle, and cohesiveness as the ratio of the area under the second compression curve to that of the first (Area2/Area1). Gumminess was calculated as hardness × cohesiveness. Chewiness and adhesiveness (negative force–time area during probe withdrawal) were not determined in the present study due to limitations in the experimental setup and raw data processing constraints. Resilience is theoretically defined as the ratio of energy recovered during the decompression phase of the first cycle to the energy applied (Area2/Area1 × 100); however, resilience values reported in this study were directly obtained from the instrument software and were not recalculated using the standardized formulation.

2.7. Sensory analysis

Sensory evaluation of the gummy samples was carried out in a standardized sensory analysis room under controlled lighting and environmental conditions (22±2 °C, white light conditions). The control gummy (without fermented *Chlorella vulgaris* biomass) and the formulations containing fermented *Chlorella vulgaris* biomass (3, 6, and 9%, w/w) were included in the tests. All samples were tempered to room temperature before serving.

A semi-trained panel of 15 panelists (n=15), consisting of food engineering and food technology students familiar with basic sensory terminology, participated in the study. The term “semi-trained” refers to panelists who received a structured training prior to the evaluation sessions. The training protocol consisted of two sessions (each approximately 60 min), including (i) introduction to sensory attributes and definitions, (ii) use of the 10-point hedonic scale, and (iii) calibration using reference samples representing low, medium, and high intensity for selected attributes (e.g., hardness, sweetness, and stickiness). Panelists were also instructed on evaluation consistency and avoidance of bias during scoring.

Demographic characteristics of the panelists were as follows: age 22.4 ± 1.8 years, with a gender distribution of 9 females and 6 males. Additionally, panelists' familiarity with microalgae-based products was assessed using a 5-point scale (1 = not familiar, 5 = very familiar), with an average score of 2.1 ± 0.9, indicating low prior exposure. Gummy samples were coded with three-digit random numbers and presented to the panelists in a randomized order. Drinking water was provided for palate cleansing between evaluations.

Panelists evaluated each sample using a 10-point hedonic scale from 0 to 9, where 0 represented "dislike extremely" and 9 represented "like extremely". The following sensory attributes were assessed: color intensity, color uniformity, transparency/opacity, surface gloss, surface smoothness, stickiness, elasticity, chewiness, hardness, mouth coating, sweetness, acidity, alg flavor intensity, aroma intensity, aftertaste, disintegration stability in the mouth, overall textural acceptability, and overall sensory acceptability (Akelom et al., 2022). All sensory data were collected individually and used for statistical analysis.

2.8. Statistical analysis

All experimental measurements were carried out in triplicate, and the results were expressed as mean ± standard deviation. Statistical analyses were performed using SPSS software (version 26.0, IBM Corp., Armonk, NY, USA). Differences among formulations were evaluated by one-way analysis of variance (ANOVA). When significant differences were detected ($p \leq 0.05$), Tukey's honestly significant difference (HSD) test was applied for multiple comparisons among means. Graphical representations were generated using R software (version 4.1.1) with the tidyverse, fmsb, and janitor packages.

3. Results and Discussion

3.1. pH, density, and °Brix content

The incorporation of fermented algae caused significant changes in the physicochemical characteristics of the gummy formulations (Table 1). Statistical analysis showed that pH, density, and °Brix values differed significantly among samples ($p < 0.05$). The pH values ranged between 5.50 and 7.98. The control sample exhibited a pH value of 6.81 ± 0.03, whereas the 3% algae formulation showed the highest pH value (7.98 ± 0.04). As the algae concentration increased further, pH gradually decreased to 6.57 ± 0.07 in the 6% formulation and to 5.50 ± 0.17 in the 9% formulation. The unusually high pH observed in the 3% algae sample appears to be associated with differences in soluble solid concentration rather than a direct buffering effect of the fermented algae itself. The °Brix value of the 3% formulation (80.42 ± 0.49%) was noticeably lower than those of the other samples (84.58–86.16%), suggesting that this formulation may have remained at a relatively lower concentration level during processing. In gummy and hydrogel-type confectionery systems, variations in soluble solid concentration may influence apparent pH values, color intensity, and matrix interactions. Therefore, the elevated pH and more vivid color characteristics observed in the 3% algae formulation may partially reflect differences arising from concentration and processing conditions rather than solely the biochemical properties of the fermented microalgal biomass.

Density values showed a decreasing trend with increasing algae concentration. The control gummies exhibited the highest density (1.42 ± 0.17 g/mL), followed by the 3% algae sample (1.39 ± 0.22 g/mL). More pronounced decreases were observed in the 6% and 9% algae formulations, with density values of 1.21 ± 0.16 and 1.18 ± 0.21 g/mL, respectively. This reduction may be associated with modifications in the gelatin–sugar matrix, including altered water distribution, increased structural porosity, and changes in gel network organization caused by algae incorporation.

Table 1. Physicochemical properties of gummy candies

Sample	*pH*	*Density (g/mL)*	*Brix Content (°B)*
Control	6.81 ± 0.03^{b}	1.42 ± 0.17^{a}	84.73 ± 0.54^{b}
3% algae	7.98 ± 0.04^{a}	1.39 ± 0.22^{a}	80.42 ± 0.49^{a}
6% algae	6.57 ± 0.07^{c}	1.21 ± 0.16^{b}	84.58 ± 0.58^{ab}
9% algae	5.50 ± 0.17^{d}	1.18 ± 0.21^{b}	86.16 ± 0.61^{c}

Data are presented as mean ± SD. Different letters in the same column indicate significant differences among samples ($p < 0.05$).

The °Brix values of the gummy samples ranged from 80.42% to 86.16%. The lowest °Brix value was observed in the 3% algae formulation, whereas the 9% algae sample exhibited the highest soluble solid content. The relatively high °Brix values observed in all formulations indicate that the gummy systems maintained the concentrated structure typical of confectionery products. Increasing algae concentration, together with reduced water addition in higher algae formulations, may also have contributed to the gradual increase in soluble solid content.

Overall, the findings indicate that fermented *Chlorella vulgaris* incorporation influenced the acid–base balance, density, and soluble solid characteristics of the gummy systems. Similar physicochemical modifications have been reported in gummy and confectionery products enriched with microalgae, where algal incorporation affected matrix organization, water distribution, and gel structure depending on concentration and processing conditions (Konar et al., 2025; Paternina et al., 2022). Previous studies have also emphasized that microalgae-derived proteins, pigments, and polysaccharides may function as techno-functional ingredients capable of modifying structural and physicochemical properties in confectionery matrices (Bartkiene et al., 2023; Maryam et al., 2024; Mosibo et al., 2024).

3.2. Color measurement

The *CIE L*a*b** color parameters of the gummy formulations are presented in Table 2. Statistical analysis demonstrated that algae incorporation significantly affected L^*, a^*, b^*, and chroma values ($p < 0.05$), whereas no significant differences were observed for hue angle (h°). The control sample exhibited the lowest lightness value (L^* = 10.86 ± 3.67), indicating the darkest appearance among all formulations. The addition of 3% fermented *Chlorella vulgaris* markedly increased lightness (L^* = 18.24 ± 2.17), resulting in a noticeably brighter and more vivid appearance. In contrast, the 6% and 9% algae formulations showed lower L^* values (11.72 ± 1.13 and 11.58 ± 1.74, respectively), which were closer to the control sample. The relatively high lightness observed in the 3% algae formulation may be associated not only with algae incorporation itself but also with the lower °Brix value of this sample compared to the other formulations. The lower soluble solid concentration may have produced a less concentrated and more translucent gel structure, thereby increasing light reflectance and visual brightness.

Positive a^* values were recorded for all samples, indicating the presence of red color components. The control formulation exhibited the lowest a^* value (1.23 ± 0.39), whereas the 3% algae sample showed a significantly higher redness value (2.58 ± 0.30). The 6% and 9% algae formulations displayed intermediate a^* values (1.63 ± 0.99 and 1.59 ± 0.23, respectively). These findings suggest that low-level algae incorporation intensified red tonal characteristics, while higher algae concentrations did not further enhance redness.

All b^* values were negative, indicating that the color profile shifted toward blue–green tones rather than yellow hues. The strongest blue–green character was observed in the 3% algae formulation (b^* = −8.94 ± 0.91), whereas the control sample exhibited the least negative value (b^* = −3.86 ± 0.65). Intermediate b^* values were observed in the 6% and 9% algae samples (−5.84 ± 0.99 and −5.47 ± 1.19, respectively). Similar to the lightness results, the more pronounced blue–green appearance observed in the 3% algae sample may partially reflect differences in soluble solid concentration and optical properties associated with the relatively lower °Brix value of this formulation.

Chroma values further confirmed the effect of algae incorporation on color saturation. The control sample exhibited the lowest chroma value (4.09±0.71), while the 3% algae formulation showed the highest chroma (9.34±0.95), corresponding to a more vivid and saturated appearance. The 6% and 9% algae formulations showed intermediate chroma values (6.05 ± 1.04 and 5.71 ± 1.17, respectively), indicating that algae incorporation generally increased color intensity compared to the control. However, the exceptionally high chroma value observed at the 3% level may also be related to differences in concentration and processing conditions reflected by the lower °Brix value.

Table 2. Color properties of gummy candies

Sample	*L**	*a**	*b**	*Chroma*	*h°*
Control	10.86±3.67c	1.23±0.39b	-3.86±0.65c	4.09±0.71c	-71.33°±4.26°a
3% algae	18.24±2.17a	2.58±0.30a	-8.94±0.91a	9.34±0.95a	-73.90°±0.94°a
6% algae	11.72±1.13bc	1.63±0.99b	-5.84±0.99b	6.05±1.04b	-74.72°±0.67°a
9% algae	11.58±1.74bc	1.59±0.23b	-5.47±1.19b	5.71±1.17b	-73.45°±3.09°a

Data are presented as mean ± SD. Different letters in the same column indicate significant differences among samples ($p < 0.05$).

The hue angle (h°) values ranged narrowly between −71.33° and −74.72°, and no statistically significant differences were observed among samples ($p > 0.05$). This finding indicates that algae incorporation primarily influenced color brightness and saturation rather than fundamentally altering the dominant hue orientation of the gummy systems.

Overall, the color measurements demonstrated that fermented *Chlorella vulgaris* incorporation modified the visual appearance of gummy candies by increasing color saturation and promoting blue–green tonal characteristics. The most pronounced visual changes were observed in the 3% algae formulation, which also exhibited the lowest °Brix value among the samples. Therefore, the color differences observed in this group may reflect not only the direct contribution of fermented microalgal pigments but also the influence of formulation concentration and processing-related variations on optical properties and light transmission within the gummy matrix.

3.3. Textural properties

The texture profile parameters of the gummy samples are presented in Table 3. Hardness values ranged from 2690.48 to 3119.85 g. The control sample exhibited a hardness value of 2957.57 ± 179.07 g, while the incorporation of 3% fermented algae slightly reduced hardness to 2690.48 ± 419.27 g. The 6% algae formulation showed the highest hardness value (3119.85 ± 5.50 g), whereas hardness decreased again in the 9% algae sample (2845.16 ± 620.00 g). Although numerical differences were observed among formulations, no statistically significant differences were detected between samples ($p > 0.05$). The relatively high standard deviation observed in the 9% formulation suggests greater structural heterogeneity at higher algae concentrations.

Cohesiveness values remained close to unity in the control (1.0053 ± 0.0039) and 3% algae samples (1.0085 ± 0.0021), indicating a relatively stable internal gel structure at low algae incorporation levels. Lower cohesiveness values were observed in the 6% (0.7680 ± 0.3394) and 9% algae formulations (0.8623 ± 0.1959), suggesting partial weakening of the internal gel network at higher algae concentrations. However, these differences were not statistically significant ($p > 0.05$). The relatively high standard deviation observed at 6% algae may indicate increased variability in gel network organization.

Gumminess values showed a decreasing trend with increasing algae concentration. The control formulation exhibited the highest gumminess value (2972.24 ± 168.19 g), while lower values were observed in the 3% (2712.80 ± 428.74 g), 6% (2394.91 ± 1052.91 g), and 9% algae formulations (2362.49 ± 148.28 g). This trend may reflect the combined influence of hardness and cohesiveness on the energy required to disintegrate the gel structure. Nevertheless, statistical analysis indicated no significant differences among the formulations ($p > 0.05$).

Similarly, resilience values changed with increasing algae concentration, from 0.8478 ± 0.0097 in the control sample to 0.8550 ± 0.0170, 0.8140 ± 0.0099, and 0.5933 ± 0.078 in the 3%, 6%, and 9% algae formulations, respectively. The 9% algae formulation exhibited a significantly lower resilience value compared with the other samples ($p < 0.05$), indicating a reduced capacity of the gummy matrix to recover after deformation. This finding suggests that higher levels of fermented *Chlorella vulgaris* incorporation may promote the formation of a more energy-dissipating and less elastic gel structure. Overall, the texture profile results indicate that fermented *Chlorella vulgaris* incorporation influenced the mechanical behavior of the gummy systems without causing statistically significant deterioration in textural quality. Similar tendencies have been reported in gummy and confectionery systems enriched with microalgae or encapsulated bioactive ingredients, where algal incorporation altered gel firmness, cohesiveness, and structural stability through modifications in hydrocolloid network interactions and water distribution (Konar et al., 2025; Paternina et al., 2022).

Table 3. Texture properties of gummy candies

Parameters	*Control*	*3% algae*	*6% algae*	*9% algae*
Hardness (g)	2957.57 ± 179.07[a]	2690.48 ± 419.27[a]	3119.85 ± 5.50[a]	2845.16 ± 620.00[a]
Cohesiveness (s)	1.0053 ± 0.0039[a]	1.0085 ± 0.0021[a]	0.7680 ± 0.3394[a]	0.8623 ± 0.1959[a]
Gumminess (g)	2972.24 ± 168.19[a]	2712.80 ± 428.74[a]	2394.91 ± 1052.9[a]	2362.49 ± 148.28[a]
Resilience (%)	0.8478 ± 0.0097[b]	0.8550 ± 0.0170[b]	0.8140 ± 0.0099[b]	0.5933 ± 0.078[a]

Data are presented as mean ± SD. Different letters in the same row indicate significant differences among samples ($p < 0.05$).

In addition, previous studies have suggested that the protein–polysaccharide composition and particle characteristics of microalgal biomass may influence gel matrix organization, depending on concentration and processing conditions (Bartkiene et al., 2023; Maryam et al., 2024). These findings support the potential use of fermented microalgae as texture-modulating ingredients in confectionery formulations.

3.4. Sensory analysis

Based on mean scores on the 0–9 hedonic scale, fermented *Chlorella vulgaris* had a limited impact on the overall sensory quality of the gummies. Statistical analysis indicated that most sensory attributes were not significantly affected by algae incorporation ($p > 0.05$), suggesting that panelists perceived the formulations as broadly similar despite compositional differences. For appearance, color intensity increased slightly with 3% and 6% algae compared with the control (from about 5.7 to >6.0) and decreased again at 9% algae, indicating that moderate supplementation can enhance color strength, whereas higher levels do not provide further benefit. Color uniformity remained within a narrow range (≈5.4–6.2) for all formulations, showing that panelists perceived the gels as generally uniform. Transparency/opacity scores were around 6.0 for the control, 3%, and 6% samples, but dropped to about 5.1 at 9% algae, suggesting a shift toward a more opaque, less glossy appearance at the highest inclusion level. A similar pattern was observed for surface gloss and surface smoothness: the control and 3% algae gummies showed the highest values, 6% algae was slightly lower, and 9% algae clearly reduced gloss and smoothness, pointing to a visually duller and less regular surface at high algae concentration. Among visual attributes, only surface gloss and surface smoothness showed statistically significant differences between formulations ($p < 0.05$), indicating that these parameters were the most sensitive to algae incorporation.

For taste and flavor attributes, the mean values were generally comparable among formulations. Aroma intensity ranged from about 5.5 in the control to 6.3 at 6% algae, implying that fermented algae can subtly reinforce the flavor profile without introducing off-notes. Sweetness scores increased from 5.3 in the control to around 5.9–6.2 at 3–6% algae and then decreased again at 9%, suggesting that low–moderate algae levels may slightly enhance perceived sweetness, while higher levels introduce vegetal notes that balance this effect. The sensory attributes of gummy candies formulated with fermented *Chlorella vulgaris* biomass are presented in Table 4.

Table 4. Sensory attributes of gummy candies formulated with fermented *Chlorella vulgaris* biomass

Attribute	*Control*	*3% algae*	*6% algae*	*9% algae*
Color Intensity	5.67 ± 2.03^{a}	6.17 ± 1.65^{a}	6.51 ± 1.47^{a}	5.94 ± 1.43^{a}
Color Uniformity	5.56 ± 2.09^{a}	5.89 ± 1.32^{a}	6.17 ± 1.51^{a}	5.39 ± 1.85^{a}
Transparency–Opacity	6.44 ± 1.89^{a}	6.03 ± 1.57^{a}	6.39 ± 1.46^{a}	5.06 ± 1.39^{a}
Surface Gloss	6.33 ± 2.03^{a}	6.06 ± 1.63^{a}	5.72 ± 1.56^{ab}	4.44 ± 1.04^{b}
Aroma Intensity	5.50 ± 1.42^{a}	5.89 ± 1.41^{a}	6.28 ± 1.45^{a}	5.83 ± 1.54^{a}
Sweetness	5.33 ± 1.81^{a}	5.89 ± 1.28^{a}	6.22 ± 1.63^{a}	5.51 ± 1.54^{a}
Acidity	5.28 ± 1.36^{a}	5.44 ± 1.34^{a}	5.56 ± 1.12^{a}	5.52 ± 0.92^{a}
Perceived Algal Flavor	5.56 ± 1.89^{a}	5.94 ± 1.39^{a}	6.06 ± 1.39^{a}	5.17 ± 1.47^{a}
Aftertaste	5.67 ± 1.19^{a}	6.06 ± 1.35^{a}	6.06 ± 1.66^{a}	5.39 ± 1.21^{a}
Hardness	6.22 ± 1.56^{a}	5.83 ± 1.47^{a}	6.28 ± 1.45^{a}	5.89 ± 1.45^{a}
Elasticity	6.01 ± 1.94^{a}	6.06 ± 1.32^{a}	6.33 ± 1.53^{a}	5.39 ± 1.53^{a}
Chewiness	6.44 ± 1.69^{a}	6.33 ± 1.57^{a}	6.06 ± 1.43^{a}	5.72 ± 1.56^{a}
Stickiness	6.22 ± 1.93^{a}	5.61 ± 1.97^{a}	6.17 ± 1.69^{a}	5.83 ± 1.69^{a}
Disintegration Stability in the Mouth	6.02 ± 1.94^{a}	6.11 ± 1.57^{a}	5.89 ± 1.45^{a}	5.39 ± 1.33^{a}
Stretchability	5.28 ± 1.84^{a}	6.06 ± 1.16^{a}	5.44 ± 1.76^{a}	4.94 ± 1.76^{a}
Surface Smoothness	7.04 ± 1.41^{a}	6.28 ± 1.53^{ab}	6.17 ± 1.58^{ab}	4.94 ± 1.63^{b}
Mouth Coating Sensation	5.94 ± 1.06^{a}	6.22 ± 1.22^{a}	6.11 ± 1.57^{a}	5.17 ± 1.62^{a}
Overall Textural Acceptability	6.28 ± 1.61^{a}	6.39 ± 0.98^{a}	6.28 ± 1.02^{a}	5.39 ± 1.14^{a}
Overall Sensory Acceptability	6.61 ± 1.72^{a}	6.50 ± 0.99^{a}	6.39 ± 1.46^{a}	5.89 ± 1.18^{a}

Values are presented as mean ± standard deviation (n = 15). Different lowercase letters within the same row indicate significant differences among formulations according to one-way ANOVA followed by Tukey's HSD test ($p < 0.05$).

Perceived acidity remained almost unchanged (≈5.3–5.6), consistent with the constant citric acid content. The "perceived algal flavor" attribute stayed in the mid-scale for all samples; 3% and 6% algae showed only a small increase compared with the control, and even the 9% formulation was described more as a mild herbal/green note than a dominant seaweed flavor. Aftertaste scores (≈5.4–6.1) were similar across formulations, indicating that fermented algae did not leave an undesirable residual taste. Mouth-coating sensation values (≈5.2–6.2) also suggested a full but not cloying oral perception, with 3% and 6% algae giving slightly higher "body" than the control. No statistically significant differences were detected among formulations for flavor-related attributes ($p > 0.05$), indicating that algae addition did not adversely affect taste perception. Textural perception was likewise only moderately affected. Hardness remained between about 5.8 and 6.3 for all samples, showing that algae addition neither markedly softened nor hardened the gel structure. Elasticity and chewiness values clustered around 6.0, with 3% and 6% algae mirroring the control and a slight decrease at 9% algae. Stickiness scores (≈5.6–6.2) confirmed that none of the formulations were perceived as excessively sticky. Disintegration and stability in the mouth (≈5.4–6.1) indicated that all gummies dissolved at an acceptable rate—neither collapsing too quickly nor persisting too long. Stretchability showed a mild optimum at 3% algae (≈6.1), with control and 6% samples slightly lower and 9% algae yielding the lowest value, suggesting that low–medium algae levels may modestly improve perceived extensibility, while excessive addition reduces it. Differences in textural perception were not statistically significant ($p > 0.05$), indicating that instrumental changes in texture were not fully translated into perceptible sensory differences.

Overall textural acceptability was very similar for the control, 3% and 6% algae gummies (~6.3), whereas the 9% formulation showed a somewhat lower, though still acceptable, score (~5.4). A comparable trend was observed for overall sensory acceptability: the control received the highest mean score (≈6.6), but 3% and 6% algae were almost identical (~6.4–6.5), indicating that moderate levels of fermented algae do not compromise consumer liking. The 9% algae sample remained above the neutrality point of the scale (~5.9) but was clearly less preferred than the other formulations. However, these differences were not statistically significant ($p > 0.05$), reinforcing that overall consumer perception remained stable across formulations.

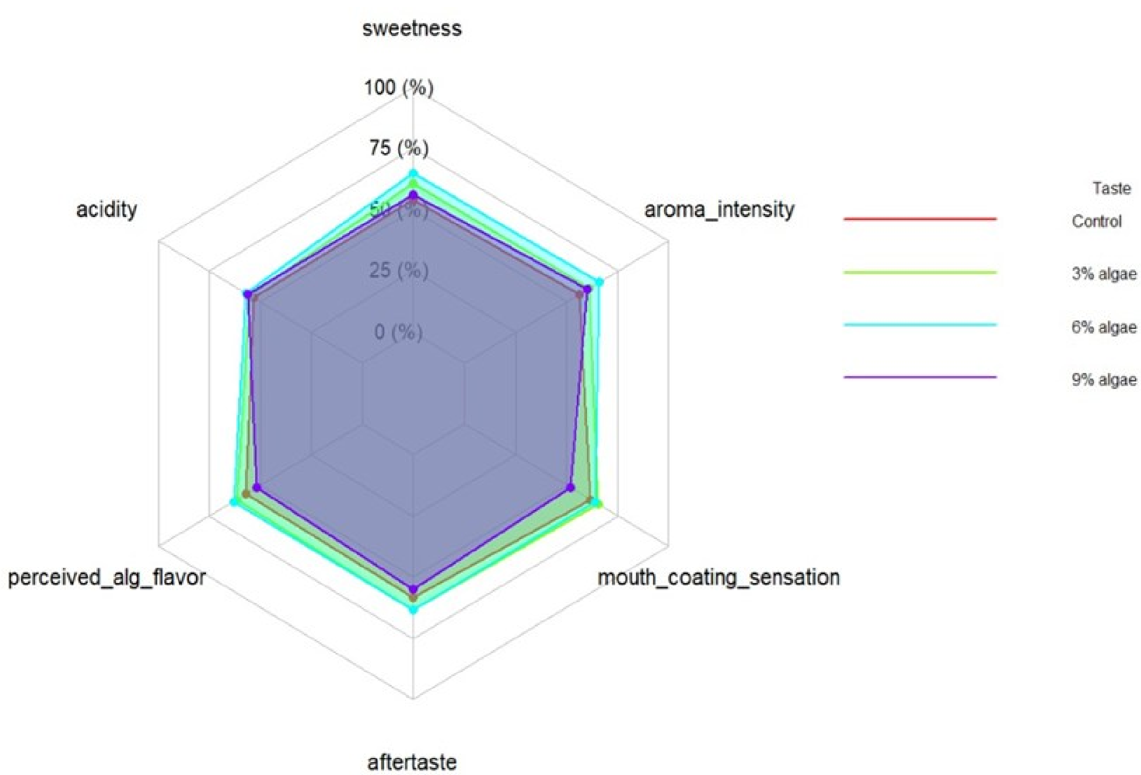

Figure 1. Radar chart of taste-related sensory attributes for gummy candies containing different algal concentrations

The multivariate patterns are illustrated by the radar plots. As shown in Figure 1, for taste-related attributes (aroma intensity, sweetness, acidity, perceived algal flavor, mouth-coating sensation, and aftertaste), the polygons of the control and algae-enriched samples largely overlap, with the 6% algae formulation forming a slightly expanded profile, suggesting a well-balanced flavor at this level.

As shown in Figure 2, the texture-related radar plot reveals almost superimposed profiles for the control, 3%, and 6% algae gummies in terms of hardness, elasticity, chewiness, stickiness, and disintegration stability, while the 9% algae sample exhibits a contracted shape, particularly along the surface smoothness and stretchability axes. This pattern indicates that high algae loading mainly impairs surface and extensibility perceptions, whereas the internal gel texture is largely preserved.

Taken together, these results indicate that incorporating fermented Chlorella vulgaris at 3–6% allows gummies to retain their characteristic color, flavor and texture while providing algal fortification, whereas 9% inclusion begins to compromise visual appearance and slightly reduces overall liking. A similar "tolerable window" for microalgal enrichment has been described in gummies and confectionery products fortified with Spirulina or mixed Spirulina–Chlorella biomass, where low-to-moderate levels improved or maintained sensory acceptance, but higher dosages led to darker appearance, more intense green notes and a gradual decline in hedonic scores (Bartkiene et al., 2023; Maryam et al., 2024; Paternina et al., 2022). In nutraceutical chewing candies rich in bio-converted Spirulina, consumers accepted a pronounced functional identity as long as sweetness, chewiness and flavor balance were preserved (Bartkiene et al., 2023), while hard candies containing microalgae remained well liked when algal flavor was perceived as mild and compatible with the sweet matrix (Maryam et al., 2024).

Our findings are consistent with these observations and suggest that, from a gastronomic perspective, microalgae-enriched gummies can be positioned either as subtly "green" products at 3–6% inclusion, or as more adventurous, algae-forward confections at higher levels, provided that visual dullness and textural roughness are carefully managed.

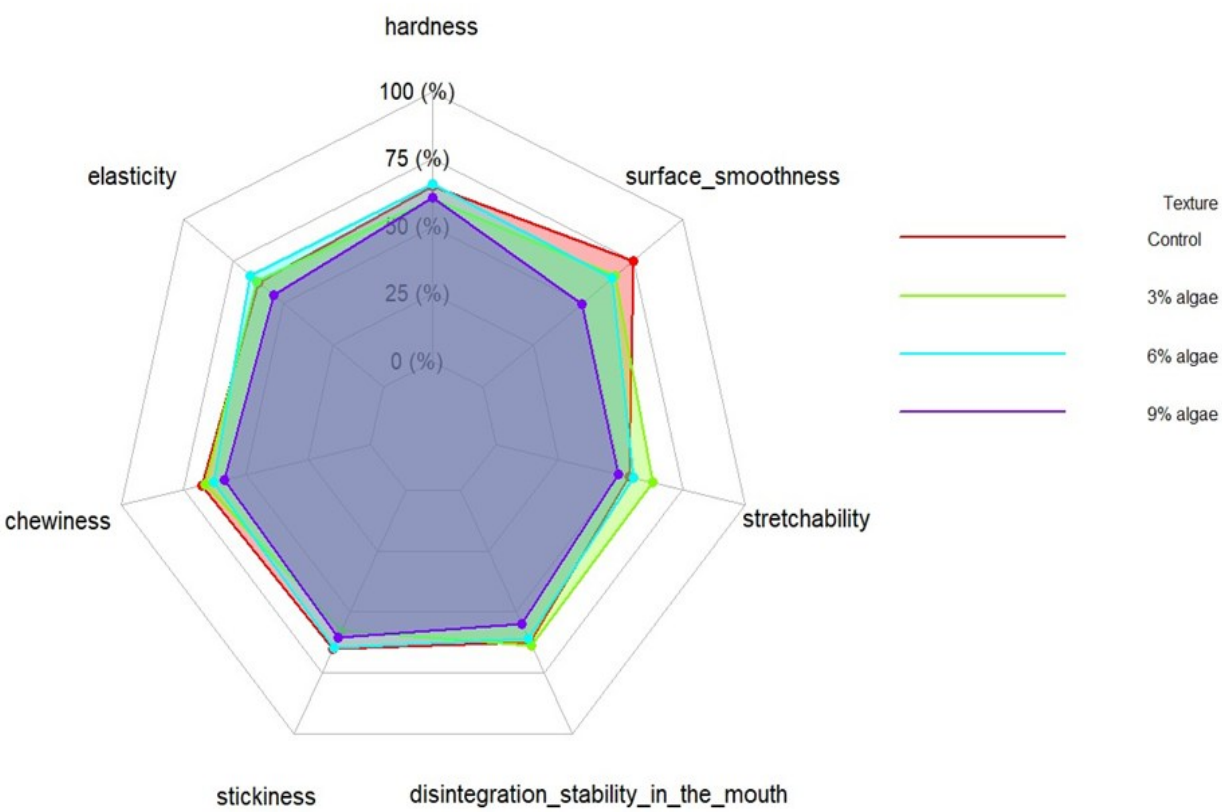

Figure 2. Radar chart of texture-related sensory attributes for gummy candies containing different algal concentrations

4. Conclusions

This study demonstrated that lactic-acid-fermented *Chlorella vulgaris* can be incorporated into gummy candy formulations as a novel techno-functional ingredient without causing major deterioration in structural or sensory quality. The incorporation of fermented microalgae at 3–9% (w/w) slightly modified pH and density while maintaining the high soluble-solid content and characteristic textural properties expected in gummy systems.

One of the most significant findings was the concentration-dependent color transformation induced by the fermented microalgae. Formulations containing 3% *Chlorella vulgaris* exhibited a vivid blue-green appearance with high chroma values, whereas higher incorporation levels resulted in darker and more opaque gels. These results indicate that fermented microalgae may serve not only as a functional ingredient but also as a natural color-modulating component in confectionery applications.

Texture profile analysis indicated that hardness and gumminess values remained within acceptable ranges for conventional gummy products. Although cohesiveness and resilience showed some variation at higher incorporation levels, the overall gel structure remained stable.

Sensory evaluation demonstrated that gummies containing 3% and 6% fermented microalgae were generally well accepted and showed quality characteristics comparable to the control formulation. While the 9% formulation exhibited a more pronounced algae-related flavor and appearance, it still remained within acceptable sensory limits.

Overall, the findings suggest that lactic-acid-fermented *Chlorella vulgaris* has potential for use in confectionery systems as a techno-functional ingredient capable of contributing color modulation and structural stability while maintaining overall sensory acceptability.

5. Limitations and Future Perspectives

Despite the promising findings obtained in this study, several limitations should be considered when interpreting the results.

First, detailed fermentation parameters, including microbial strain composition, fermentation temperature, and processing duration, could not be disclosed due to proprietary restrictions associated with the supplier's patented production process. Consequently, strict reproducibility of fermentation-related effects remains limited.

Second, the present study primarily focused on physicochemical, textural, and sensory characteristics of the gummy formulations. Direct compositional and bioactive analyses, such as protein characterization, pigment quantification, total phenolic content, antioxidant activity, or chlorophyll stability, were not performed within the scope of this work. Therefore, conclusions regarding the potential nutritional or functional properties of the fermented microalgae should be regarded as preliminary. Future studies should include comprehensive biochemical characterization under controlled fermentation conditions.

Third, sensory evaluation was conducted using a semi-trained panel consisting of food science students (n = 15). Although this approach is suitable for preliminary product evaluation, the relatively limited panel size and participant profile may not completely reflect broader consumer preferences. Future research should include larger consumer groups with diverse demographic backgrounds as well as trained sensory panels to improve external validity.

Finally, certain methodological limitations related to texture profile analysis should also be acknowledged. Parameters such as chewiness and adhesiveness were not determined within the scope of the present study. In addition, resilience values were evaluated based on instrument software outputs, which may limit direct methodological comparability with studies using manually standardized calculations. Variability observed in some measurements may also partially reflect sample heterogeneity and methodological constraints.

Future studies should therefore employ a complete TPA parameter set together with standardized analytical and data-processing protocols to improve analytical robustness and inter-study comparability.

Declarations

Competing Interest

The authors declare that they have no financial or non-financial competing interests.

Funding

This research received no external funding.

Ethics Statement

This study involved laboratory analyses and a non-invasive sensory evaluation of gummy candy samples. The sensory evaluation was conducted with volunteer panelists for product acceptability assessment. Participants were informed about the purpose and scope of the evaluation, and their voluntary consent was obtained prior to participation. All procedures were conducted in accordance with ethical research principles.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

AI statement

Generative AI tools were used only in a limited and controlled manner for language editing. All content was reviewed and approved by the authors.

Author's Contributions

C. Güner (0000-0002-7935-4674): Conceptualization, methodology, investigation, formal analysis, data curation, writing – original draft, writing – review and editing.

S. Pekdoğan Göztok (0000-0002-6589-1217): Conceptualization, methodology, investigation, formal analysis, data curation, writing – original draft, writing – review and editing.

Authors contributed equally to this study and have read and agreed to the published version of the manuscript.

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