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Characterization of nutritional and textural properties of vegan Kiwi jelly enriched by *Spirulina* extract

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ABSTRACT: *Recent concerns have been raised about the health and nutrition implications of jelly snacks. This study aimed to create enriched vegan kiwi jellies by adding 0% to 3% Spirulina extract and assessing their nutritional, textural, and sensory qualities. The addition of Spirulina to the Carrageenan-Kiwi jelly resulted in increased protein content (0.26 to 1.95 g/100g), mineral levels (0.33 to 1.74 g/100g), and antioxidant capacity (11.55 to 32.35 and 6.97 to 19.46 for DPPH and ABST^{+}, respectively). However, the color variables L*, b*, and C* decreased significantly with increasing microalgae levels (from 82.00 to 26.32, 76.00 to 32, and 86.42 to 39.4, respectively), resulting in a darker jelly sample. The incorporation of Spirulina extracts also influenced the behavior of the Carrageenan-Kiwi jelly, as evidenced by the investigation of rheological parameters such as storage modulus (G'), loss modulus (G''), complex modulus (G*), loss tangent (tanδ) and dynamic viscosity (η) versus frequencies. All samples showed a consistent gel-like structure as the prevalent behavior, with a dominant difference of about one logarithmic unit between G' and G'', indicating a consistent gel-like structure as the prevalent behavior. The calculated Tanδ (G''/G') for all samples was found to be less than one, indicating the viscoelastic solid nature of the samples. The curves of η and G* versus frequency did not exhibit any significant transition or frequency dependency. The most consistent behavior was observed in the more fortified S2 and S3 samples, confirming the positive role of Spirulina in strengthening the Kiwi gel structure. The textural data obtained from the force-time curve (hardness, adhesiveness, springiness, and chewiness) were measured in the ranges of 2.6-4.75 N, 0.0029-0.002 N.m, 21.91-19.62 mm×10^{-1}, 0.14-0.19 N, 0.5-0.5 N, and 9.9-17 mJ, respectively. The best textural parameters were observed in the sample S2 and S3, which contained more Spirulina, supporting the rheological data. However, the sensory evaluation of the enriched jelly indicated a negative effect on sensory attributes such as flavor, texture, taste, color, and overall acceptability index. The most appreciated jelly was the control sample, with an acceptability index of 92%, while the most enriched jelly sample (S3), containing 3% microalgae, was also within the approving range with an acceptability index of 72%. Despite these observations, Spirulina could be a viable option for developing healthier Carrageenan-Kiwi jelly. Further research is necessary to understand the gel formation mechanism in Spirulina's presence and improve sensory attributes.*

KEYWORDS: *kiwi jelly, rheological properties, Spirulina sp., texture*

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INTRODUCTION

Snack food consumption has historically provided delightful interludes and diverse flavor experiences between main meals, becoming a burgeoning trend irrespective of age, gender, and social standing in the 21st century [1]. As consumer responsibility for personal, community, and environmental well-being has heightened, demands for nutritious, organic, plant-based snacks without synthetic additives have led to the emergence of "Good Health Snack (GHS)" items within the global market [1, 2, 3]. This transition has seen the burgeoning consumption of fiber-enriched fruit-based products among health-conscious millennials, estimating a Compound Annual Growth Rate (CAGR) of 8.68% in the fruit snack market from 2021 to 2028 [4].

The Kiwi (*Actinidia deliciosa*) is a fruit known for its appealing taste, low caloric content, and abundant vitamin C and bioactive compounds, including antioxidants, insoluble fiber, carotenoids, flavonoids, and minerals. In addition to its widespread consumption as fresh fruit for its health benefits, preparing it into industrialized foods such as jams, juices, smoothies, jellies, drinks, and dried snacks is very popular [5]. For example, a portable Kiwi jelly can provide benefits such as desirable texture, value-added, and excellent stability compared to fresh fruit. Considering Iran's significant production of Kiwi, processing this fruit into value-added products like enriched Kiwi jellies could be a viable strategy. However, in many countries including Iran, synthetic dyes in jellies are preferred due to their stability and low cost. Synthetic dyes could be associated with symptoms such as cancer and hyperactivity [6]. As a result, there is a high demand for healthy generation and vegan-based and clean-label foods. In this context, *Arthrospira platensis* micro-algae, referred to as *Spirulina*, has been introduced by food biotechnology and is considered a nutraceutical due to its diverse bioactive secondary metabolites, pigments (carotenoids, phycobilin), and balanced chemical composition [7]. Additionally, replacing animal-derived gelatin with another microalgae kappa-carrageenan could be another strategy to meet the needs of vegan consumers and produce a stable gel over a wide range of temperatures, as well [8]. *Ferreira et al.* did indeed review the history of using *Spirulina* as a natural colorant and enrichment ingredient in various food products, including jellies, shakes for the elderly, extruded snacks, feta cheese, white chocolate, and pasta. Moreover, carrageenan is utilized in a range of dairy and non-dairy products such as chocolate milk, frozen desserts, cheese, ice cream, instant products, jellies, and various sauces, where it functions as a gelling, stabilizing, and viscosity-building agent [9]. The literature suggests that consuming algae and vegan products like jellies can be a healthy alternative and may contribute to preventing certain diseases and serving as immune modifiers, antifungals, and antivirals [10]. However, incorporating *Spirulina* extract may affect some aspects of the physicochemical parameters of vegan jelly. Texture defects and water seepage during storage have been reported [11]. While the physicochemical and sensorial properties of jelly products have been extensively documented by several researchers, the rheological properties of enriched jellies have received limited attention, with most studies focusing on cereal-based products [12]. Considering this gap, this study aimed to develop a novel, natural vegan-based Kiwi jelly by incorporating microalgae. This study investigated various parameters of the jelly, including color, rheological properties (texture), antioxidant capacity (DPPH and $ABTS^{+}$), and descriptive sensory analysis. Given the expectation that the impact of *Spirulina* would not significantly affect the behavior of other variables, the one factor at a time (OFAT) approach was selected as a more straightforward and practical method [13, 14] to focus on the effect of *Spirulina* on the carrageenan jelling system. In this study, the parameters of jelly such as color, rheological properties, texture analysis, antioxidant capacity (DPPH and $ABTS^{+}$), and descriptive sensory analysis were investigated. To our knowledge, this study has not yet been carried out.

MATERIAL AND METHODS

Raw material

Spirulina was purchased from a local biotechnology company (Reihan, Iran).

The gross chemical composition (% DW) of the microalgae biomass was as follows: 43.88% protein, 2.61% fat, 16.35% carbohydrates, and 31.06% ashes.

Kiwi (*Actinidia deliciosa*) are prepared from the local market. The carrageenan utilized was sourced from the (Philippines), while anhydrous citric acid from (Kimia Shimi, Razi, Iran), was employed to adjust the pH to 3.2. Food-grade sucrose and bottled water, both sourced from the same batch, were purchased at the local market.

Concentration and extraction processes

The extraction and concentration processes are performed according to *Garrido et al.* description [15]. Briefly, Kiwis were crushed and diluted (1:1 w/w) with water and then pressed, and centrifuged. Desired total soluble solids were adjusted by adding sucrose and then boiling and evaporating in an open pan. The optimum pH was adjusted by adding anhydrous citric acid. Each sample was hot-filled into sanitized glass jars. All jelly samples were prepared from the same Kiwi juice concentrated batch. *Spirulina* extract was prepared by dissolving 5 grams in 100 ml of water and heating it in the microwave. The use of microwave technology to extract compounds from algae has been identified as an efficient and cost-effective process [16].

Jelly sample preparation

Four jelly formulations (C, S1, S2, S3) were prepared as shown in Table 1.

Table 1. Ingredients of jellies formulation (C, S1, S2, S3), containing (0, 0.75, 1.5, and 3%) of *Spirulina* sp. respectively.

Ingredient	C	S1	S2	S3
Juice proportion (g/kg)	500	500	500	500
Carrageenan g/kg	0.85	0.85	0.85	0.85
Spirulina extract (ml)/kg	0	1.5	3	6
Synthetic color (ml/kg)	1 cc	0	0	0
Final total solid (g/kg)	705	702	697	706

C sample as control sample without *Spirulina sp.*, and S1, S2, and S3 samples containing 0.75%, 1.5%, and 3% of *Spirulina* extract, respectively. The proportion of sample ingredients and the percentage level of *Spirulina* were selected according to previously reported [17]. The mixture was boiled to concentrate around 70 °Brix. Finally, each sample was hot-filled at about 90 °C into sanitized and labeled glass jars, which were cooled to room temperature to set the gel structure. Then, they were sealed and stored for later measurements.

Nutritional composition and antioxidant capacity

The proximate composition of protein, lipid, and ash was determined according to the Association of Official Analytical Chemists (AOAC, 1995). Carbohydrates were quantified by difference [18].

Preparation of Kiwifruit jelly extracts for antioxidant assay

The 2 g of jelly samples were weighed and subjected to two extraction processes at room temperature. The first extraction involved stirring the samples with 100 mL of a methanol: water mixture (80:20 v/v) for 1 hour, while the second extraction involved stirring with 100 mL of acetone: water mixture (70:30 v/v) for 1 hour with intermittent centrifugation at 4,000×g for 15 minutes. The resulting supernatants were then transferred to volumetric flasks, and 80% methanol was added to each sample to bring the total volume to 200 ml [19].

Antioxidant Activity Test with DPPH Radical

Each 20 µl extract was mixed with 180 µl of the DPPH solution at room temperature, and the absorbance at 517 nm was determined after 30 minutes. The antioxidant capacity of each sample was determined by comparing its absorbance to a calibration curve and reported as Trolox equivalents per gram (µmol TE/g) [20].

Antioxidant Activity Test with ABTS Radical

Each 20 µL extract was mixed with 180 µL of the $ABTS^{+}$ solution at room temperature, and the absorbance was recorded at 734 nm after 10 minutes. The antioxidant capacity of each sample was quantified in terms of Trolox equivalents per gram (µmol TE/g) [20].

Color analysis

The surface of Kiwi jellies was assessed using a spectrophotometer (Hunter Lab, colorflex EZ, England) to determine their CIELAB coordinates (L*, a*, b*), with calibration performed using a white surface. In this color coordinate system, the L* value represents lightness on a scale from 0 (black) to +100 (white). The a* value indicates the color's position on the red-green axis, ranging from –100 (green) to +100 (red), while the b* value represents the position on the blue-yellow axis, ranging from –100 (blue) to +100 (yellow). Subsequently, using the specified formula, ΔE, hue angle (h*), and chroma or intensity (C*) were computed based on the collected data [21].

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (1)$$

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (2)$$

$$h^* = tan^{-1}(\frac{b^*}{a^*}) \quad (3)$$

Rheological properties

The rheological characteristics were evaluated using a Paar Physica MCR 301 rheometer (Anton Paar GmbH, Graz, Austria) equipped with a parallel plate setup (diameter d=50 mm) and temperature control via the Peltier system. Each sample was placed on the rheometer plate at 20.0 ± 0.1°C, with a 2 mm gap created by lowering the plate. The excess sample was removed, and the edges were sealed with paraffin oil. After allowing the sample to relax stress and stabilize temperature for 15 minutes, measurements were taken. The linear viscoelastic region was determined by observing the behavior of storage G' and loss G″ moduli under stress levels ranging from 0.1 to 100 Pa at a fixed frequency of 1 Hz. Dynamic oscillations were conducted at 0.5 or 1% strain within the linear viscoelastic region (LVR) and at angular velocities (ω) ranging from 0.1 to 100 rad/s to calculate the elastic (G') and viscous (G″) moduli. The complex modulus (G*) and complex viscosity (η*) for each sample were then computed using the provided formula based on the collected data.

$$\eta^* = \frac{G^*}{\omega} \quad (4)$$

$$(G' + iG'' = G^*) \quad (5)$$

$$\tan\delta = \frac{G''}{G'} \quad (6)$$

Where G′ is the storage modulus (Pa), G″ is the loss modulus (Pa), and ω is the angular velocity (rad/s).

Textural analysis

The analysis was conducted one-week post-gelation when the gel strength had stabilized to ensure no additional alterations like shrinkage, chemical interactions, or other reactions had taken place. The measurements were conducted at a constant temperature of 25 °C. The jellies were poured into food containers to create cylindrical specimens measuring 25 mm in height. Subsequently, these jelly samples were compressed in the axial direction

using a cylindrical probe (25 mm in diameter) at 50% deformation, with a displacement rate of 25 mm/min to determine the texture profile properties. Following this, the probe was retracted to its initial position, and a second compression cycle was performed on the same sample. All assessments were carried out in triplicate for accuracy.

Statistical analysis

The experiments were replicated three times, and the results were expressed as mean ± standard deviation (SD). Statistical analysis was conducted using Minitab (version 19) through a one-way analysis of variance (ANOVA). Variances between mean values were deemed significant at a P-value of less than 0.05, except for sensory data, which were evaluated at a significance level of $P < 0.01$.

RESULTS AND DISCUSSION

Nutritional composition of enriched kiwi jellies

The nutritional content of kiwi jellies supplemented with *Spirulina* is presented in Table 2.

Table 2. The nutritional content and antioxidant capacity of kiwi jellies supplemented with spirulina .The same letters indicate non-significant differences (P<0.05) for mean values within the same column.

Treatments	TS	Protein (g 100/g)	Carbohydrate (g 100/g)	Ash (g 100/g)	Lipids (g 100/g)	DPPH EC50*	ABST+ EC50*
C	68.1±1.5	0.26±0.21 [d]	66.05±2.4 [a]	0.33±0.1[d]	0.28±0.03[b]	11.55±0.27 [d]	6.97±0.12 [d]
S1	69.2±0.8	0.53±0.3 [c]	67.68±0.7[a]	0.66±0.2[c]	0.26±0.02[b]	25.99±0.13 [c]	10.48±0.32 [c]
S2	69.5±1.0	0.94±0.6 [b]	67.3±1.6[a]	0.98±0.1[b]	0.35±0.05[a]	28.38±0.21 [b]	14.21±0.32 [b]
S3	70.4±0.9	1.95±0.5 [a]	66.5±0.8[a]	1.74±0.3[a]	0.31±0.1[a]	32.35±0.22 [a]	19.46±0.17 [a]

* µmol of torolox equivalent/g FW

The most enriched sample with *Spirulina* (S3) contained significantly higher amounts of protein, lipid, ash, and antioxidant activity.

The enhancements in nutritional aspects, specifically protein, lipid, and ash contents, observed in this research align with findings from prior studies on different food items enriched with *Spirulina.*

For example, increased protein and ash content were observed in pasta [22], and wheat flour [23]. Additionally, there was a notable increase in antioxidant capacity when *Spirulina* extract was included in the jelly. The jelly containing 3% *Spirulina* extract (S3) exhibited the greatest antioxidant activity, nearly three times more than the control jelly. These results are consistent with *Almeida et al.* on various functional foods [24], and they concluded that the antioxidant activity of products was influenced by the percentage of *Spirulina*. However, there are discrepancies in the observed antioxidant capacity levels among researchers, which could be attributed to factors such as distinct attributes of the samples under examination, the specific algae species, geographical provenance, or even environmental fluctuations. Despite these potential influences, *Spirulina* is known for its rich nutritional content, including protein, vitamins, minerals (iron, calcium, magnesium, manganese, potassium, and zinc), essential fatty acids, and polyphenols [25].

Color attributes

The effect of adding *Spirulina* extract on color parameters a*, b*, L*, ΔE, C*, and h* at the end of storage is presented in Table 3.

Table 3. The effect of adding spirulina extract on color parameters a*, b*, L*, ΔE, C*, and h* at the end of storage. Non-significant differences (P<0.05) are indicated by the same letters for mean values within the same column

Treatments	*a**	*b**	*L**	*ΔE*	*C**	*h**
C	*-41.00±4.36 [c]*	*76.00±3.61 [a]*	*82.00±3.46 [a]*	*0*	*86.42±1.4 [a]*	*-1.08±0.04[ab]*
S1	*-33.67±3.06 [b]*	*71.33±1 [b]*	*87.00±3.42 [a]*	*11.73±2.58 [c]*	*79.2±0.83[b]*	*-1.13±0.03[bc]*
S2	*-22.67±2.56 [a]*	*55.00±0.57 [c]*	*74.66±0.58 [b]*	*23.95±2.32 [b]*	*59.51±3.97[c]*	*-1.18±0.03 [c]*
S3	*-22.00±2.65 [a]*	*32.67±2.8 [d]*	*26.33±2.52 [c]*	*40.12±2.35 [a]*	*39.47±1.06 [d]*	*-0.98±0.08[a]*

A* value was measured at about -41 (green color), shifting to -22 with the addition of *Spirulina*, indicating a move toward the green end of the spectrum, which could be due to a strong green component. Chlorophyll, a dominant pigment isolated from Spirulina biomass, serves as a natural green dye and possesses antioxidant, antibacterial, wound-healing, and anti-mutagenic properties [26]. The b* ranged from about 76 to 32, demonstrating decreased yellow intensity and increased blue intensity. It has been mentioned that in high concentrations of *Spirulina platensis* extract, the phycocyanine pigment with a characteristic blue color increases [6]. There was a significant decrease in L* from about 82 to 26, demonstrating that *Spirulina* leads to darkening. Similar results were reported in *Spirulina*-enriched yogurt, ice cream, and functional jam [27, 28, 29]. The measured ΔE showed a high difference between the treatments. Values of 6 and 12 and above can be considered criteria for distinguishing groups of colors and a noticeable difference, respectively. This finding should be well-thought-out commercially for producing naturally colored kiwi jellies to cater to vegetarian, kosher, and halal consumption.

Dynamic test

Small-amplitude oscillatory tests (SAOS), encompassing strain sweep and frequency sweep, are widely utilized to identify the linear viscoelastic region (LVE) and evaluate the elastic properties of mature gels [30]. These tests also enable the exploration of the impact of additives and treatment variables on the viscoelastic behavior of products during storage. Parameters, such as storage modulus (G'), loss modulus (G″), complex modulus (G*), loss tangent (tanδ= G″/G'), and dynamic viscosity (η*), serve as indicators of a material's viscoelastic response. G' and G″ indicate the elasticity and viscosity characteristics, respectively, whereas the loss tangent indicates the proportionate impact of the viscous and elastic elements in dynamic assessments.

In the strain sweep experiments conducted on kiwi jelly samples, a strain amplitude of 0.01–100% at a constant frequency of 1.0 Hz and 25°C was employed. The storage modulus (G'), loss modulus (G″), and tanδ of all samples remained strain-independent up to approximately 1% strain, indicating a linear viscoelastic region where stress is relational to applied strain [19]. The double logarithmic plot of storage modulus G', loss modulus G″, and tanδ as a function of frequency within this linear region is demonstrated in Figures 1a, b, c, and d.

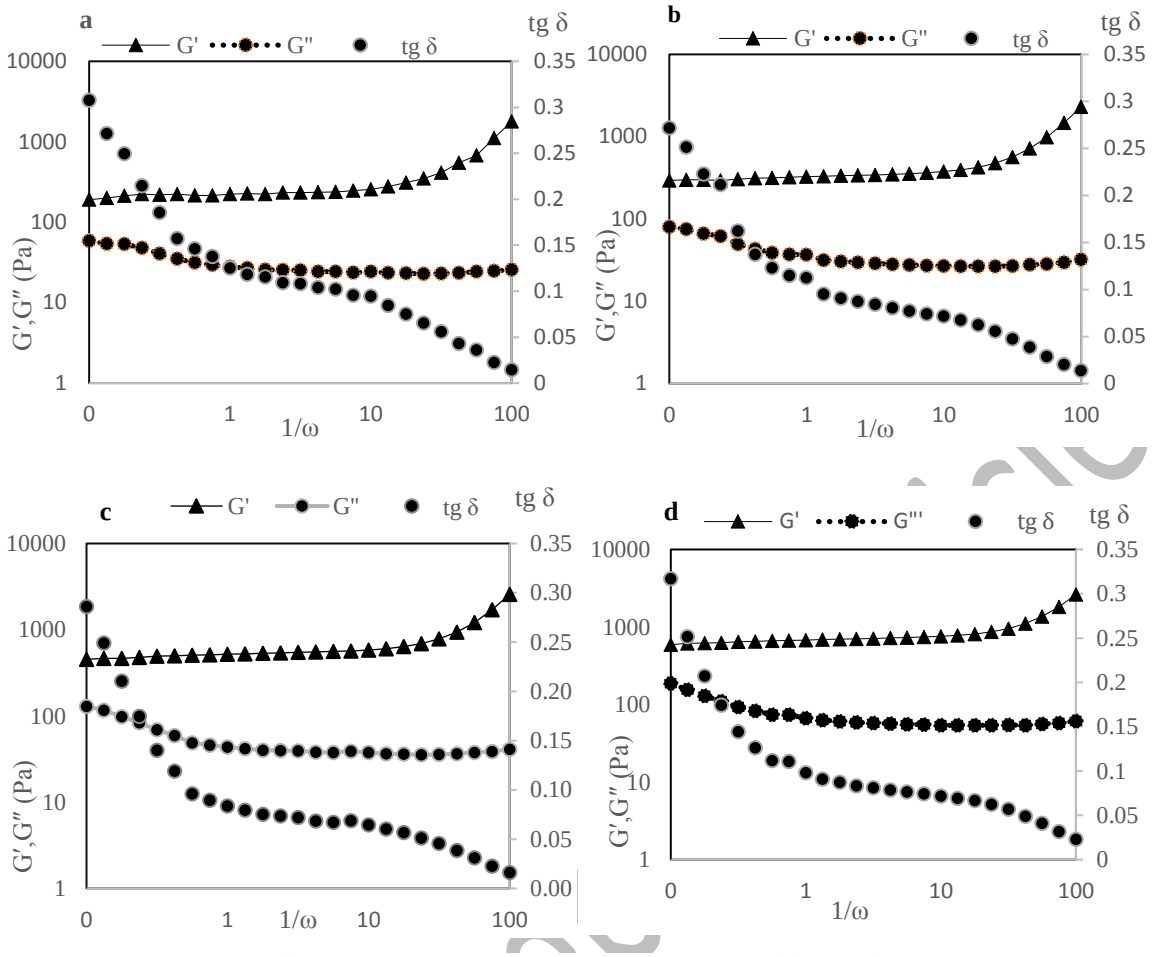


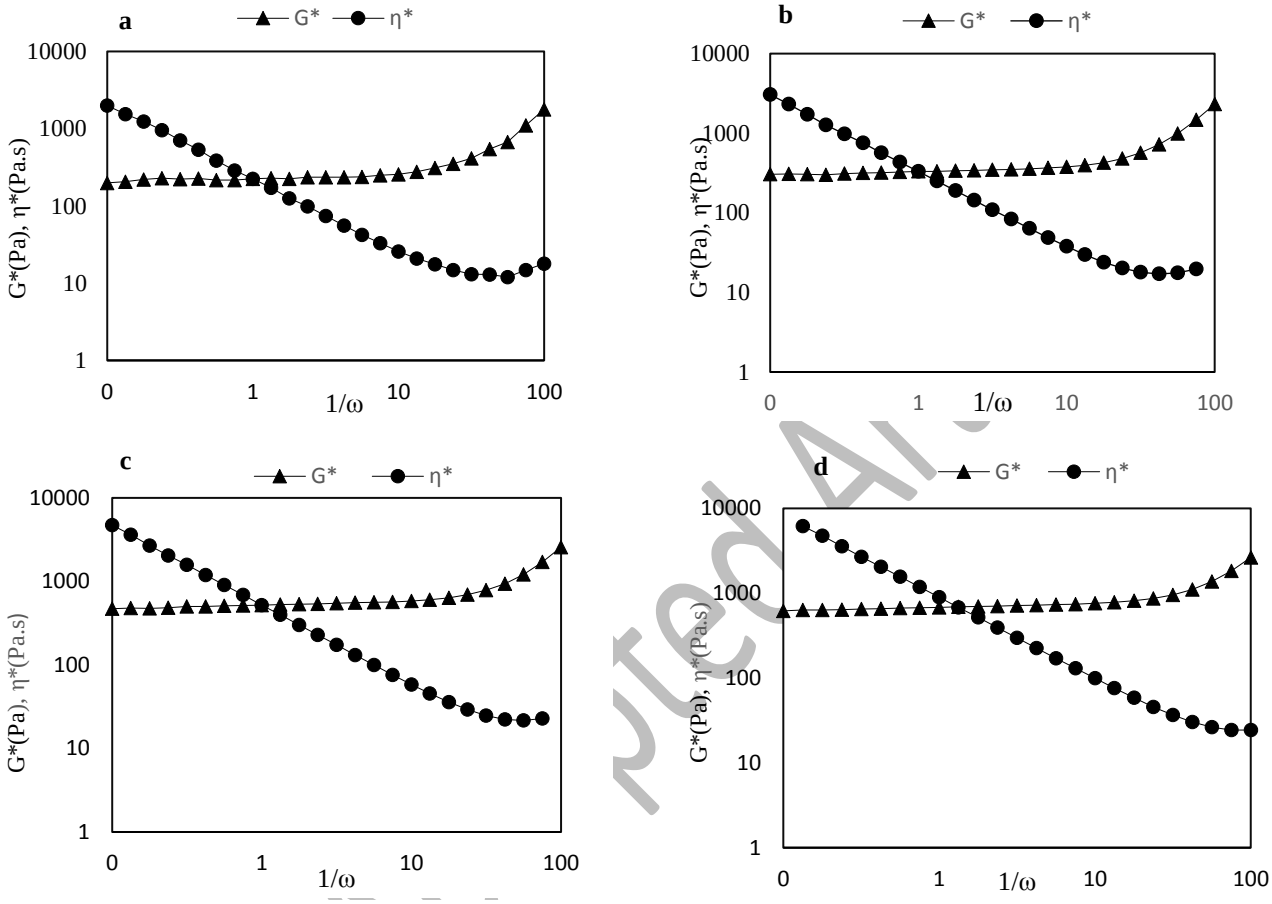
Fig 1. The double logarithmic plot of storage modulus G', loss modulus G″, and tanδ as a function of frequency from 0.1 Hz to 100 Hz. a. 0% Spirulina (C), b. 0.75% Spirulina (S1), c. 1.5% Spirulina (S2), d. 3% Spirulina (S3).

As can be seen a consistent dominance of approximately one logarithmic unit of G' over G″ for all samples, indicating a prevalent gel-like structure. Additionally, the absence of crossover points in the curves further confirms this consistent gel-like behavior. Furthermore, tanδ (G″/G') values below one for all samples support the viscoelastic nature of the gels [30].

A gentle linear increase and a gradual linear rise of log (G') with log (1/ω) were observed for all cases, indicative of weak gels. The rheological character of gels has been previously explained by *Figueroa and Genovese* in fruit jams and jellies [31], and by *Sayko et al.* in polysaccharide solutions [32]. It is also evident that the S2 and S3 jellies showed elevated values of viscoelastic properties (G' and G″) compared to the jellies without Spirulina (C) and the S1 sample, even though the frequency dependence was alike. This indicates that, although the S2 and S3 jellies were also weak gels, they were stronger than the C and S1 jellies. The reduction in the slope of the graph at high frequencies demonstrates the shear-thinning phenomenon, particularly pronounced for the blank sample and S1 sample, while slight frequency dependencies were observed for the

fortified S2 and S3 samples. A double logarithmic plot of complex moduli (G*) and dynamic viscosity (η*= G*/ω) as a function of strain amplitude at different frequencies for all samples is presented in Figures 2 a, b, c, and d.

Fig 2. The double logarithmic plot of complex modulus G*, and η* as a function of frequency from the 0.1 Hz to 100 Hz. a. control sample 0% Spirulina (C), b. 0.75% Spirulina (S1), c. 1.5% Spirulina (S2), d. 3% Spirulina (S3)



It is evident that the complex modulus increased and the dynamic viscosity decreased with frequency, exhibiting weak gel characteristics. Additionally, both the complex modulus and complex viscosity of the most fortified samples (S2 and S3) were higher and exhibited significantly enhanced rheological properties compared to those of the control and S1 samples. As the only changing factor among the samples was the percentages of *Spirulina*, the strengthening of the gel structure could be related to the carrageenan-*Spirulina* interaction. This finding aligns with previous research conducted by *Batista et al.*, and *Uribe-Wandurraga et al.* which declared the rheological moduli (G' and G″) of weak carrageenan gels significantly increased after the addition of *Spirulina* [33, 11]. Carrageenan gels are created through the bonding of double helices at the molecular level, forming stable and structured aggregates. The cooling-induced formation of these double helices strongly relies on the existence of electrolytes, particularly potassium, calcium, and sodium, respectively [34]. *Spirulina* microalgae contains significant amounts of these minerals originating from its inherent chemical makeup and remnants of the culture media [35]. This can elucidate the role of microalgae in the substantial increase in k-carrageenan gel rheological moduli.

However, the formation of a weaker gel structure was reported by *Gouveia et al.* in *Spirulina*-starch gel, *Batista et al.* in the *Spirulina*-pea protein-carrageenan-starch system, and *Fallah and Kafili* in carrageenan-*Spirulina* apple jelly [33, 36, 37]. This phenomenon may be related to the presence of starch in the mentioned experimental

systems and the intrinsic apple starch, which may compete with microalgae for water-binding sites during gelation. Also, the less firm gel structure could potentially be attributed to the direct use of *Spirulina* powder and the impact of its substantial particles on network disturbance [38]. In addition, the effective extraction of *Spirulina* extract containing more cations may have influenced the creation of a more robust three-dimensional gel structure [16].

Textural properties

Texture Profile Analysis (TPA) involves the double compression of a food sample in a vertical direction, simulating the action of the jaw [38, 39]. The parameters of texture profile analysis, concerning *Spirulina* concentrations, are detailed in Table 4.

Table 4. Parameters for texture profile analysis as a function of *spirulina* concentrations. Non-significant differences (P<0.05) are indicated by the same letters for mean values within the same column

	C	S1	S2	S3
Hardness (N)	**2.61±0.15 ^{c}**	**4.07±0.12 ^{b}**	**4.34 ± 0.1 ^{ab}**	**4.75 ± 0.26 ^{a}**
Adhesiveness (J*10^{-3})	**1.9 ± 0.13 ^{c}**	**2.0 ± 1.01^{c}**	**2.5 ± 0.09^{b}**	**2.8 ± 0.15^{a}**
Springiness (m*10^{-4})	**19.62 ± 0.61^{c}**	**21.26 ± 0.14 ^{b}**	**22.62 ± 0.24 ^{a}**	**21.91± 0.84 ^{ab}**
Cohesiveness (N*10^{-3})	**0.19 ± 0.34 ^{a}**	**0.18 ± 0.12 ^{a}**	**0.15 ± 0.04 ^{b}**	**0.14 ± 0.08 ^{b}**
Gumminess (N)	**0.50 ± 0.16 ^{b}**	**0.59 ± 0.06 ^{b}**	**0.67 ± 0.18 ^{a}**	**0.75 ± 0.14 ^{a}**
Chewiness (N*10^{-3})	**9.90 ± 0.96 ^{d}**	**12.60 ± 0.92 ^{c}**	**14.70 ± 1.06 ^{b}**	**17.00 ± 1.26 ^{a}**

The results of the one-way ANOVA statistical analysis indicated that incorporating *Spirulina* had a significant impact ($p \leq 0.05$) on the hardness, springiness, cohesiveness, gumminess, and chewiness of Kiwi jellies.

Hardness, which is characterized as the peak force during the initial compression cycle and mirrors the force required to compress food between molars in the first bite, ranged from 2.6 to 4.75 N, with the highest value observed for the S3 sample. This finding suggests that the addition of *Spirulina* (at 3% in the S3 sample) could enhance the stability of the fragile junction of the carrageenan double helix by introducing K^{+} ions, resulting in a more robust and solid gel [40]. These observed parameters fell within the range of apple jellies [15, 37], were higher than Kiwi jellies with maltodextrin and lemon grass (0.234-0.263 N) [41], and lower than ginger-carrageenan-pectin jellies (9.12-10.33 N) [42].

The samples exhibited a range of adhesiveness values from 1.9 (C) to 2.8 mJ (S3). Adhesiveness, representing the work required to overcome adherence forces between the food surface and the mouth, teeth, and lips in sensory analysis [43], was notably higher in the S3 sample. Previous studies have indicated that jellies with higher hardness tend to have increased adhesiveness [44], a correlation that was also observed in the current study.

Springiness, or elasticity, denotes the relative spring-back of food samples and is calculated as the ratio of recoverable to total compressive deformation, ranging from 1.96 (C1) to 2.26 mm (S2). The measured springiness values were higher than those reported for coconut jelly blended with pomegranate juices (0.91-0.92 mm) [45] and grass jelly (0.88 ± 0.04 mm) [46], indicating a firmer texture. While springiness typically correlates with gel hardness, the values in this study did not align with the trend observed for hardness, with S2 displaying the highest elasticity instead of S3. This discrepancy may be attributed to a harder structure leading to increased resistance to compression, reduced deformation, and diminished recovery after compression. Similar findings were reported by *Musavi et al.* regarding composite gels [35].

Cohesiveness, serving as an indicator of structural integrity, is determined by the force required to remove a probe from the product mass [38]. This parameter inversely reflects the rate at which the food fractures during mechanical operations. Although there was a minor variation in cohesiveness values, varying from 0.19 to 0.14 mJ, the highest value was observed for the C and S1 jelly samples. This may be due to the more viscous nature of

the C sample, resulting in less fracturing compared to the other samples. Low cohesiveness which makes food easier to chew and swallow [47], was observed in the jellies with higher *Spirulina* content. Similar observations were made on Physalis jellies (0.033 to 0.176 N) [48]. Gumminess and chewiness are scientific terms used to describe the texture of semi-solid and solid foods, respectively. Given the semi-solid and solid nature of the samples in this study, both parameters were evaluated. Gumminess describes the energy needed to break down viscoelastic foods during ingestion [38]. The gumminess values of the jellies ranged from 0.5 (C) to 0.75 N (S3), showing a consistent increase in line with the trends observed for hardness and cohesiveness. Similar findings were reported by *Peng et al.*, where variations in gumminess values were linked to firmness and cohesiveness [49].

Chewiness represents the energy needed to chew a solid food into a form suitable for swallowing, with values increasing from 9.9 to 17 mJ in this study, corresponding to the trends in hardness and gumminess. When the level of hardness and gumminess is elevated, chewiness also tends to be high [50]. Overall, incorporating *Spirulina* with carrageenan led to a significant increase in hardness, gumminess, and chewiness values. These results align with the trends observed in dynamic rheology studies.

Sensory analysis

The statistical analysis of results is presented in Table 5.

Table 5. Sensorial data of the samples with different levels of *spirulina* microalgae (C, S1, S2, S3). Means values in the same column that are accompanied by the same letters are not statistically different (P<0.01)

	C	S1	S2	S3
Flavor	**4.6 ± 0.51^{a}**	**4.3 ± 0.48^{a}**	**4.4±0.51^{ab}**	**3.8 ± 0.92^{b}**
Taste	**4.7 ± 0.48^{a}**	**4.2 ± 0.63^{ab}**	**4.0±0.51^{bc}**	**3.5 ± 0.97^{c}**
Color	**4.9 ± 0.32^{a}**	**4.3 ± 0.48^{b}**	**4.2±0.63^{bc}**	**3.7 ± 0.80^{c}**
Texture	**4.3 ± 0.48^{a}**	**4.2 ± 0.42^{a}**	**4.1±0.31^{ab}**	**3.7 ± 0.67^{b}**
Overall acceptability	**4.7 ± 0.48^{a}**	**4.3 ± 0.48^{ab}**	**4.1±0.31^{b}**	**3.6 ± 0.51^{c}**
AI (Acceptance Index) %	**94%**	**96%**	**82%**	**72%**

It is indicated that incorporating *Spirulina* significantly ($p < .05$) influenced the sensorial traits of texture, taste, aroma, color, and overall acceptance, as the S3 sample containing the highest level of *Spirulina* received the lowest sensory scores.

The obtained texture scores also verified the evaluation of instrumental parameters of hardness, which decreased by increasing *the Spirulina* level. However, despite the decreasing evaluating scores of the S3 sample, its acceptance index was calculated at 72% confirming its overall acceptability. A product is accepted concerning its sensorial characteristics if its acceptance index is higher than 70% [3]. Thus, we can conclude that *Spirulina*-enriched Kiwi jelly with good sensory acceptability can be produced. Contradict results were reported by *Lucas et al.*, who didn't recognize a significant difference for the attributes evaluated of blank and 2.6% *Spirulina*-enriched snacks, except for the color feature ($p<0.05$) [1]. They reported a high total color difference $\Delta E=30.5$ among them. Reducing sensory scores of *Spirulina-enriched* products were reported by *Özbal et al.* on white chocolate, Kevin *et al.* on cookies, and *Pandey et al.* on Kiwi-Pomegranates jellies [51, 52, 53].

The enriched snacks, such as the vegan kiwi jellies developed in this study, demonstrated increased protein content, mineral levels, and antioxidant capacity, providing consumers with an alternative that offers improved nutritional benefits while maintaining the gel-like structure characteristic of traditional jellies. However, further investigations are needed to elucidate the mechanisms that underlie gel formation in the presence of *Spirulina*, with a focus on understanding how the microalgae interact with the jelly matrix to influence its structural and textural properties. Additionally, future studies should aim to address the sensory challenges observed in the

enriched jellies, with an emphasis on improving attributes such as flavor, texture, taste, and color to enhance overall consumer acceptability. Moreover, exploring the potential diversification of enriched jellies with other fruit bases and alternative vegan gelling agents could offer valuable insights into expanding the range of functional jelly products. By delving into these areas, future research endeavors can contribute to the development of innovative, nutritious, and appealing jelly products that align with evolving consumer demands for healthier snack options. Additionally, designing another study based on DOE is currently in progress, as it can provide a more comprehensive understanding of the relationships between variables.

CONCLUSIONS

In conclusion, this study suggests that *Spirulina* is a promising addition to increase nutrient content and improve the functional properties of natural kiwi jellies including increased protein levels, mineral content, and antioxidant capacity. Additionally, the incorporation of *Spirulina* into the jellies resulted in improvement in both rheological and textural properties, demonstrating compatibility within the kappa-carrageenan-*Spirulina* gel system.

Despite the positive effects such as a consistent gel-like structure with enhanced strength, especially in samples with higher *Spirulina* concentrations, the sensory evaluation indicated a negative impact on attributes such as flavor, texture, taste, and color, affecting overall acceptability.

The study highlights the potential of *Spirulina* as a beneficial additive for enhancing the nutritional profile and structural properties of Carrageenan-Kiwi jelly. Therefore, it could be considered an opportunity for a value-added strategy in processing this nutritious fruit, offering a range of benefits for both consumers and the food industry. Further research is needed to optimize the sensory aspects and understand the gel formation mechanism in the presence of *Spirulina* for the development of healthier and more accepted jelly products.

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