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Research Article

Evaluating the Feasibility of Using Glasswort (*Salicornia herbacea* L.) Powder as a Salt Substitute in Meatball Production

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Abstract: This study aimed to investigate the effects of partial substitution of sodium chloride (NaCl) with glasswort (*Salicornia herbacea* L.) powder on the physicochemical, textural, and sensory properties of meatballs. Five formulations were prepared by replacing NaCl (0.5-1.0%) with varying levels of glasswort powder (2-4%). The results indicated that replacing NaCl with glasswort powder significantly decreased the moisture content and increased the ash content of meatballs ($p<0.05$), while protein and fat contents remained unaffected ($p>0.05$). The pH values increased slightly with the addition of glasswort powder, particularly in the GP14 treatment. Cooking loss was significantly reduced in samples containing glasswort ($p<0.05$). Color parameters revealed decreased lightness (L^*) and redness (a^*), and increased yellowness (b^*) values, resulting in darker product color. Textural analysis showed higher hardness values in most glasswort-added samples, consistent with their lower moisture content. Sensory evaluation results demonstrated that higher levels of glasswort powder led to lower acceptability scores, mainly due to changes in color and flavor. Overall, the study suggests that glasswort powder can serve as a promising natural salt replacer in meat products, enhancing some properties while supporting sodium reduction goals.

Keywords: Glasswort, NaCl, Salt substitute, Meatball

Köfte Üretiminde Tuz İkamesi Olarak Deniz Börülcesi (Salicornia herbacea l.) Tozunun Kullanılabilirliğinin Değerlendirilmesi

Öz: Bu çalışmanın amacı, sodyum klorürün (NaCl) kısmen deniz börülcesi (*Salicornia herbacea* L.) tozu ile değiştirilmesinin köftelerin fizikokimyasal, tekstürel ve duyusal özellikleri üzerindeki etkilerini araştırmaktır. Beş farklı köfte formülasyonu hazırlanmış ve NaCl (%0.5-1.0) yerine farklı oranlarda (%2-4) deniz börülcesi tozu eklenmiştir. Sonuçlar, NaCl'nin deniz börülcesi tozu ile değiştirilmesinin köftelerin nem içeriğini azalttığını, kül içeriğini artırdığını ($p<0.05$), protein ve yağ içeriği üzerine ise önemli bir etkisinin olmadığını göstermiştir ($p>0.05$). pH değerleri özellikle GP14 uygulamasında olmak üzere deniz börülcesi tozu ilavesiyle hafif artış göstermiştir. Deniz börülcesi içeren örneklerde pişirme kaybı önemli düzeyde azalmıştır ($p<0.05$). Renk parametreleri, açıklık (L^*) ve kırmızılığın (a^*) azaldığını, sarılığın (b^*) ise arttığı ve ürün renginin koyulaştığını ortaya koymuştur. Tekstürel analizler, deniz börülcesi ilaveli örneklerin çoğunda, daha düşük nem içeriğine uygun olarak, daha yüksek sertlik değerleri olduğunu göstermiştir. Duyusal değerlendirme sonuçları, deniz börülcesi tozunun daha yüksek seviyelerinin, özellikle renk ve tat değişiklikleri nedeniyle genel kabul edilebilirlik puanlarını düşürdüğünü göstermiştir. Genel olarak çalışma, deniz börülcesi tozunun et ürünlerinde umut verici doğal bir tuz ikamesi olarak kullanılabileceğini, bazı özellikleri iyileştirirken sodyum azaltımı hedeflerini de desteklediğini göstermektedir.

Anahtar Kelimeler: Deniz börülcesi, NaCl, Tuz ikamesi, Köfte

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1. Introduction

Meatball is among the most consumed foods by consumers of all age groups worldwide owing to its simple preparation, affordable prices, and attractive sensory properties (Soyocak et al., 2024). Hundreds of different types of meatballs are produced and consumed by adding various ingredients to the meat and using different cooking techniques. In Türkiye, there are approximately 290 different types of meatballs, varying according to regions and masters. The main reasons for these differences are the various types of meat used in production, different ingredients added to the meatball mixture, the technological processes the meat undergoes, and the cooking techniques (Sarıcaoğlu & Turhan, 2013). Salt (NaCl) has been one of the most widely used ingredients in the processing of meat products for centuries (Seong et al., 2017).

NaCl serves as a crucial multifunctional additive in comminuted meat systems, contributing to flavor enhancement, texture development, and product preservation. Its ability to decrease water activity effectively suppresses microbial activity, thereby extending product shelf life (Desmond, 2006; Gaudette & Pietrasik, 2017; Fieira et al., 2018). However, excessive sodium intake has been directly associated with hypertension, cardiovascular diseases, and other metabolic disorders (He & MacGregor, 2009; Lim et al., 2015). In response to these health concerns, the World Health Organization (WHO) and various national health authorities have recommended reducing sodium intake to below 5 g of salt per day (WHO, 2023). Consequently, the food industry has focused on developing alternative strategies to lower sodium levels in processed foods while maintaining product quality.

Reducing salt in meat products, however, remains a technological challenge because NaCl reduction often negatively affects texture, flavor, juiciness, and microbial stability (Ruusunen & Puolanne, 2005). Numerous approaches have been explored to compensate for these drawbacks, including the use of mineral salts (Fieira et al., 2018), flavor enhancers (Gaudette & Pietrasik, 2017; dos Santos Alves et al., 2017), hydrocolloids (Li et al., 2023), and plant-based ingredients (Choi et al., 2015; Lim et al., 2015; Seong et al., 2017). Among these alternatives, halophytic plants have recently attracted attention for their natural saltiness and high mineral content, offering a more natural and health-oriented approach to sodium reduction in meat products.

Glasswort (*Salicornia herbacea* L.) is a halophytic plant that thrives in saline coastal environments and naturally accumulates significant amounts of sodium, potassium, calcium, and magnesium (Kim et al., 2014a). Owing to its mineral composition, dietary fiber, phenolic compounds, and antioxidant properties, glasswort has been used in functional foods and as a natural seasoning agent (Choi et al., 2015; Lim et al., 2015). Its characteristic saline taste makes it a potential natural salt replacer, while its bioactive compounds may provide additional health benefits. Furthermore, the use of glasswort aligns with current trends toward clean-label and natural food ingredients, as consumers increasingly prefer minimally processed products without synthetic additives.

Several studies have examined the incorporation of glasswort into processed meat products, particularly in sausages, frankfurters, cured ham, and beef jerky. For example, Lim et al. (2015) observed that *Salicornia herbacea* powder could be used to improve the sensory quality and microbial safety of sun-dried Hanwoo beef jerky. Kim et al. (2014a) reported that the addition of 1.5 glasswort enhanced the textural properties of frankfurters formulated with 0.75% NaCl, while Kim et al. (2014b) and Choi et al. (2015) observed improved cooking yield and reduced cooking loss in glasswort-added formulations. Lim et al. (2015) also demonstrated that using glasswort hydrates in reduced-sodium, reduced-fat frankfurters maintained acceptable physicochemical characteristics. In study by Seong et al. (2017), it was reported that replacing 50% of NaCl with glasswort powder in four different dry-cured pork cuts, including Bulgi (semimembranosus, semitendinosus, and adduct muscles), Seolgit (biceps femoris muscle), Dogani (quadriceps femoris muscle), and Boseop (middle gluteal and gracilis muscles), did not cause any defects in the technological quality, color, texture, and sensory quality of the finished products. More recently, Jin et al. (2025) found that substituting part of NaCl with *Salicornia herbacea* powder improved cooking yield and textural properties in emulsified and semi-dried sausages. However, the application of glasswort powder in traditional meat products such as meatballs has not been extensively studied, and its effects on compositional, physicochemical, and sensory characteristics remain largely unknown.

Therefore, this study aimed to evaluate the feasibility of using glasswort powder as a partial substitute for sodium chloride in meatball production. Specifically, the effects of replacing NaCl with different levels of glasswort powder on the physicochemical, textural, and sensory properties of meatballs were investigated. The findings are expected to contribute to the development of healthier meat formulations that meet sodium reduction goals while maintaining consumer acceptability and technological performance.

2. Materials and Methods

2.1. Materials

Fresh glassworts (*Salicornia herbacea* L.) used as a salt replacer in the study were collected from Ortaca, Muğla (Türkiye), and powdered using a Waring-8011ES blender (Stamford, USA) after drying in an oven at 40 °C. The resulting glasswort powder (moisture 4.67%) was stored at 4 °C until usage. The minced beef (moisture 59.86%, protein 18.56%, fat 20.26%, and ash 0.87%), beef fat (moisture 3.52%, fat 95.58%), garlic powder, stale bread, and NaCl were supplied from a local market in Samsun, Turkey. The moisture content of glasswort powder, the moisture, protein, fat, and ash content of ground beef, as well as the moisture and fat content of beef fat, were determined according to the procedures specified in AOAC (2000). All analytical-grade reagents utilized in the study were obtained from Sigma-Aldrich (St. Louis, MO, USA).

2.2. Preparation of meatballs

Five different treatments were included in the experimental design, and the first treatment, which contained 1.5% NaCl but not glasswort powder, was taken as the control treatment (CON). The second treatment was composed of 0.5% NaCl and 2.0% glasswort powder (GP52), the third treatment was 0.5% NaCl and 4.0% glasswort powder (GP54), the fourth treatment was 1.0% NaCl and 2.0% glasswort powder (GP12), and the fifth treatment was 1.0% NaCl and 4.0% glasswort powder (GP14) (Table 1).

Table 1. Formulation of meatballs by partially substituting NaCl with glasswort powder.

Ingredients (%, w/w)	**Treatments**[1]				
	CON	**GP52**	**GP54**	**GP12**	**GP14**
Minced beef	67.5	66.5	64.5	66.0	64.0
Beef fat	15	15	15	15	15
NaCl	1.5	0.5	0.5	1.0	1.0
Glasswort powder	-	2.0	4.0	2.0	4.0
Stale bread	15	15	15	15	15
Garlic powder	1.0	1.0	1.0	1.0	1.0
Total	100	100	100	100	100

[1] CON, 1.5% NaCl without glasswort powder (control); GP52, 0.5% NaCl and 2.0% glasswort powder; GP54, 0.5% NaCl and 4.0% glasswort powder; GP12, 1.0% NaCl and 2.0% glasswort powder; GP14, 1.0% NaCl and 4.0% glasswort powder.

Each treatment was mixed for 10 min to achieve uniform distribution, then portioned into approximately 30 g samples and formed into patties with a thickness of 10 mm and a diameter of 50 mm. Analysis of the meatballs was initiated on the production day, and the meatballs were kept at 4 °C until the study was completed to prevent spoilage. The experiment was carried out in two replications on different days, and triplicate analyses were performed for each replicate.

2.3. Compositional and physicochemical characterization of meatballs

Moisture, protein, fat, and ash contents of the CON, GP52, GP54, GP12, and GP14 treatments were analyzed following the procedures described in the AOAC (2000) official methods. Briefly, the moisture amount was determined as a percentage based on the weight loss of approximately 5 g of sample after drying at 105 °C until a constant weight was reached. For the determination of protein content, the nitrogen content of samples was first determined using a Kjeldahl-based Kjeltec nitrogen determination apparatus, and the protein amount was then calculated by multiplying this value by the conversion factor of *6.25*. The fat content was measured by extracting fat from approximately 5 g of sample using a Soxhlet extraction apparatus with anhydrous diethyl ether, followed by evaporation of the ether, drying of the ether extract, cooling, and weighing. The ash content was determined based on the weight loss obtained by incinerating 3-5 g of sample in a muffle furnace at 550 °C until no brown residues remained. Proximate composition analyses were carried out in triplicate.

The water holding capacity (WHC) of meatball samples was assessed via a modified press method based on Öztan and Vural (1993). A 1.0 g sample was put down on filter paper (Whatman No. 1), positioned between two Plexiglas plates, and compressed for 1 hour using a 1.0 kg weight. The areas corresponding to the meat film and the exuded liquid were measured with a Type KP-21 planimeter (Japan). WHC was calculated as the ratio of the pressed sample area to the total area, where an increased ratio denoted enhanced water retention capacity.

The pH values of the meatballs were determined using a Cyberscan PC 510 pH meter (Singapore) equipped with a Sensorex S175CD Spear Tip electrode (USA). Calibration was performed at 25 °C with standard buffers of pH 4.01 and 7.00.

Cooking loss was quantified as a percentage using the method described by Turhan et al. (2005). First, the raw samples were weighed. They were then cooked on a preheated Arçelik brand electric grill (Türkiye) for a total of 7 min, 5 min on one side and 2 min on the other. After cooking, the samples were cooled down to room temperature for 30 min and then reweighed. The cooking loss was calculated using the following equation:

$$\text{Cooking loss (\%)} = \frac{\text{Uncooked meatball weight - Cooked meatball weight}}{\text{Uncooked meatball weight}} \times 100 \qquad (1)$$

2.4. Instrumental color and texture profile analysis of meatballs

Color evaluation was performed on meatball surfaces at ambient temperature using a Minolta CR-400 colorimeter (Japan) calibrated with a standard white tile under a C illuminant at a 2° observer angle. Measurements included L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness) values, corresponding to scales from 0 to 100 for lightness and -60 to +60 for the chromatic parameters.

Texture profile analysis (TPA) was conducted according to the method outlined by Öztürk and Turhan (2020) using a TA-XT Plus Texture Analyzer (UK) with a 25 mm cylindrical aluminum probe (P/25) and a 2 kg load cell. Samples (approximately 30 mm in diameter and 15 mm in height) underwent double compression at pre-test, test, and post-test speeds of 2.0, 5.0, and 5.0 mm/s, respectively, with a 5-second interval between compressions and 10 mm deformation. The parameters hardness (N), springiness (mm), cohesiveness, and chewiness (N·mm) were derived from the force–time curves generated by the Texture Exponent 32 software.

2.5. Sensory evaluation of meatballs

A sensory panel of 10-12 trained assessors evaluated the samples for appearance, flavor, tenderness, and juiciness under controlled fluorescent lighting conditions. Meatballs were cooked for total 7 min on a preheated Arçelik brand electric grill (Türkiye), cooled to room temperature, portioned, and served to panelists in randomized order. Appearance was assessed on raw samples, while cooked samples were evaluated for flavor, tenderness, and juiciness. Attributes were scored on a nine-point hedonic scale (1 = dislike extremely, 9 = like extremely). Overall acceptability was calculated as the average of the four parameters, each equally weighted (25%) (Turhan et al., 2014).

2.6. Statistical analysis

Data analysis was carried out using SPSS v21 (IBM, Chicago, IL, USA). One-way ANOVA was used to evaluate treatment effects, and when significant ($p<0.05$), means were separated by Duncan's multiple range test. Results are reported as mean ± standard deviation.

3. Results and Discussion

3.1. Compositional and physicochemical properties of meatballs

The compositional and physicochemical properties of meatballs produced by partially substituting NaCl with glasswort powder are presented in Table 2. As shown, replacing NaCl with glasswort powder decreased the moisture content of meatballs and increased the ash content ($p<0.05$), while it had no significant effect on fat and protein contents ($p>0.05$). Except for GP52, all other treatments exhibited lower moisture values compared to the control group. In GP54 and GP14 treatments, which contained 4% glasswort powder, the ash content was found to be higher than that of the control. However, all meatball samples remained within the compositional limits specified in the Turkish Uncooked Meatball Standard (TSE, 2002). The observed changes in moisture and ash content are likely due to the inherent composition of glasswort powder. Additionally, differences in the minced beef content of the treatments may also have contributed to these changes. Previous studies have also reported that adding glasswort or plant-based additives to meat products may lead to a decrease in moisture content and an increase in ash content. For example, Choi et al. (2015) observed that the moisture content of reduced-salt frankfurters containing 1.5% NaCl decreased from 61.51% to 56.81% in those containing 1.0% NaCl and 1.0% glasswort, while the ash content increased from 1.52% to 1.61%. In line with these findings, Jeon and Choi (2012) observed that the addition of seaweed (green laver, sea mustard, and seaweed fusiforme) powders to pork patties decreased their moisture content while increasing their crude ash content, and Yeşilyurt and Turhan (2025) reported similar effects when fig peel (*Ficus carica* L.) powder was incorporated into beef patties.

WHC is a crucial characteristic of proteins in comminuted meat products (Ergezer et al., 2014), and the amount and denaturation of proteins influence it (Serdaroğlu et al., 2005). The WHC of the meatball samples ranged from 0.85 to 0.90, and replacing NaCl with glasswort powder in meatball production had no statistically significant effect on WHC ($p>0.05$) (Table 2). This outcome could be attributed to the lack of any statistically significant differences in the protein content of the meatballs made with partial substitution of NaCl with glasswort powder. Several studies have indicated that non-meat components do not alter the WHC of meat products. For example, Lim et al (2015) reported no significant ($p<0.05$) difference between the WHC values of frankfurter with glasswort hydrate containing isolated soy protein or sodium caseinate and control frankfurter. Similarly, Yeşilyurt and Turhan (2025) reported that adding fig peel powder to beef meatballs did not change the WHC values. Contrary to the findings of the current study, there are also some reports that bread crumbs (Ergezer et al., 2014), dried pumpkin pulp and seed (Serdaroğlu et al., 2018), and peanut (*Arachis hypogea* L.) skin (Bıyık & Turhan, 2022) used in meatball production improve WHC. Depending on the level of addition, these plant-derived ingredients can improve the WHC of the final product by keeping moisture in the matrix of restructured or formed meat products (Turhan et al., 2009).

Replacing NaCl with glasswort powder affected the pH values of the meatball samples, and all treatments containing glasswort powder generally exhibited higher values than the control meatballs. However, this increase was only significant in the GP14 treatment ($p<0.05$) (Table 2). This state could be attributed to the pH value of the glasswort powder used in the study, which was determined to be 6.14. Similarly, Jeong et al. (2020) reported that replacing NaCl with red glasswort increased the pH values of pork loin, and Choi et al. (2015) reported that the frankfurters with 1% NaCl and 1% glasswort powder exhibited higher pH values compared to the control frankfurters containing 1.5% NaCl. Also, Lim et al. (2015) observed that frankfurter with glasswort hydrate containing carboxy methyl cellulose or isolated soy protein or sodium caseinate exhibited a higher pH value than the control sample.

Cooking loss occurs due to the evaporation of moisture and loss of fat. As presented in Table 2, the cooking loss values of the meatball samples ranged from 37.57% to 42.43%, and this variation was found statistically significant ($p<0.05$). The control group exhibited the highest cooking loss, whereas replacing NaCl with glasswort powder significantly reduced cooking loss ($p<0.05$). Nonetheless, the reduction observed in the GP52 treatment was not statistically significant ($p>0.05$). Accordingly, the partial replacement of NaCl with glasswort powder in meatball formulations decreased cooking loss and thereby enhanced cooking yield. This effect could be attributed to the ability of starch present in glasswort powder to absorb the water released during cooking, which could not be retained by denatured proteins (Aykin Dinçer et al., 2018). This finding is consistent with those reported by Jin et al. (2025), who demonstrated that the incorporation of Salicornia herbacea powder improved the yield of emulsified and semi-dried sausages. Similarly, Kim et al. (2014a) observed that increasing the proportion of glasswort in reduced-sodium frankfurters resulted in improved cooking yield by reducing cooking loss.

Table 2. Compositional and physicochemical properties of meatballs by partially substituting NaCl with glasswort powder[1].

Parameters	Treatments[2]				
	CON	GP52	GP54	GP12	GP14
Moisture (%)	52.10±0.08^{a}	51.24±0.77^{a}	47.45±0.04^{c}	48.55±0.07^{b}	46.94±0.30^{c}
Protein (%)	15.02±0.42^{a}	14.41±0.74^{a}	14.06±0.02^{a}	14.32±0.37^{a}	13.92±0.01^{a}
Fat (%)	24.77±0.84^{a}	25.03±0.78^{a}	25.58±0.65^{a}	25.41±0.64^{a}	25.86±0.05^{a}
Ash (%)	2.38±0.16^{cd}	2.24±0.16^{d}	3.19±0.14^{b}	2.70±0.13^{c}	3.66±0.26^{a}
WHC[3]	0.88±0.01^{a}	0.88±0.03^{a}	0.85±0.01^{a}	0.90±0.01^{a}	0.89±0.01^{a}
pH	6.10±0.03^{b}	6.12±0.02^{b}	6.17±0.04^{ab}	6.13±0.02^{b}	6.22±0.03^{a}
Cooking loss (%)	42.43±0.33^{a}	41.91±0.98^{a}	39.17±0.61^{b}	38.07±0.62^{bc}	37.57±0.05^{c}

[1] Results are the means ± standard deviations from two replicates and three analyses per replicate. Means with different superscripts (a-d) in the same row are significantly different at $p<0.05$.
[2] CON, 1.5% NaCl without glasswort powder (control); GP52, 0.5% NaCl and 2.0% glasswort powder; GP54, 0.5% NaCl and 4.0% glasswort powder; GP12, 1.0% NaCl and 2.0% glasswort powder; GP14, 1.0% NaCl and 4.0% glasswort powder.
[3] WHC, Water holding capacity.

3.2. Instrumental color and texture profile of meatballs

Color is a primary quality attribute that strongly influences consumer perception, purchasing behavior, and satisfaction with meat products (Turhan et al., 2017). L^*, a^*, and b^* values of meatballs were within the range of 50.86-58.40, 3.31-15.26, and 18.38-22.19, respectively, and they were affected by replacing NaCl with glasswort powder ($p<0.05$) (Table 3). Replacing NaCl with glasswort powder decreased the L^* and a^* values, while increasing the b^* values. All treatments exhibited lower L^* and a^* values compared to the control meatballs, whereas only the GP54 and GP14 treatments showed higher b^* values than the control. Thus, the color of the meatballs containing glasswort powder as a substitute for NaCl became darker compared to the control meatballs. The decrease in lightness and redness values is an expected outcome, as additives with low lightness and redness reduce the L^* and a^* values of the products to which they are added, resulting in a darker color. In fact, the glasswort powder used in this study exhibited a low L^* value of 62.89 and a low a^* value of -8.12, which consequently contributed to the darkening of the product color. These observations agree with Kim et al. (2014b), who found that glasswort addition reduced L^* and a^* values while elevating b^* values in reduced-salt sausages. Likewise, Lim et al. (2015) reported decreased lightness and redness in raw and cooked frankfurters formulated with glasswort hydrate, carrageenan, isolated soy protein, or sodium caseinate. Also, Jeon & Choi (2012) found similar results when they added marine algae powders to patties.

The textural properties of the meatballs showed values ranging from 27.31 to 37.00 N for hardness, 0.72 to 0.90 mm for springiness, 0.23 to 0.26 for cohesiveness, and 5.30 to 7.49 N·mm for chewiness. However, the variation in these properties was significant only for hardness ($p<0.05$), as shown in Table 3. Except for the GP12 treatment, the meatballs with glasswort powder exhibited distinctly higher hardness values than those of the control sample. The increased hardness could be attributed to the lower moisture content of the meatballs containing glasswort powder (Table 2), as observed in previous studies. Furthermore, it is also considered that the dietary fiber present in glasswort is responsible for the increased hardness (Kim et al., 2014b). For example, Kim et al. (2014a) reported that the incorporation of glasswort powder led to increased hardness in reduced-salt frankfurters. In line with this, Jin et al. (2025) also observed a significant rise in hardness when glasswort powder was used as a partial substitute for NaCl in sausages.

Table 3. Color properties and textural profile of meatballs by partially substituting NaCl with glasswort powder[1].

Parameters	Treatments[2]				
	CON	GP52	GP54	GP12	GP14
Color property					
*L**	58.40±0.54^{a}	51.89±0.72^{bc}	50.86±0.30^{c}	53.31±0.84^{b}	50.87±0.66^{c}
*a**	15.26±0.71^{a}	5.67±0.42^{b}	3.49±0.49^{c}	6.31±0.81^{b}	3.31±0.04^{c}
*b**	18.38±0.87^{b}	19.83±0.64^{b}	22.19±0.84^{a}	19.62±0.29^{b}	21.83±0.54^{a}
Textural profile					
Hardness (N)	27.31±3.34^{b}	37.00±5.17^{a}	36.89±5.25^{a}	27.40±3.28^{b}	35.71±4.82^{a}
Springiness (mm)	0.90±0.08^{a}	0.86±0.10^{a}	0.87±0.17^{a}	0.72±0.19^{a}	0.76±0.13^{a}
Cohesiveness	0.25±0.04^{a}	0.24±0.03^{a}	0.23±0.02^{a}	0.26±0.04^{a}	0.23±0.05^{a}
Chewiness (N·mm)	6.17±1.57^{a}	7.49±0.79^{a}	7.31±1.92^{a}	5.30±2.15^{a}	6.35±2.07^{a}

[1] Results are the means ± standard deviations from two replicates and three analyses per replicate. Means with different superscripts (a-c) in the same row are significantly different at $p<0.05$.
[2] CON, 1.5% NaCl without glasswort powder (control); GP52, 0.5% NaCl and 2.0% glasswort powder; GP54, 0.5% NaCl and 4.0% glasswort powder; GP12, 1.0% NaCl and 2.0% glasswort powder; GP14, 1.0% NaCl and 4.0% glasswort powder.

3.3. Sensory evaluation

Sensory evaluations of meatballs produced by partially substituting NaCl with glasswort powder are displayed in Figure 1. As seen, substituting NaCl with glasswort powder led to a decrease in all sensory scores ($p<0.05$), but this decrease was not significant for appearance in the GP12 treatment and for juiciness in the GP52 treatment ($p>0.05$).

Treatments GP54 and GP14, which contained higher amounts of glasswort powder, generally received lower scores for all sensory parameters. These results were probably due to unfamiliarity with the green color and the unique flavor of glasswort. Such negative effects of glasswort on the sensory properties were also reported by various researchers. For example, Choi et al. (2015) reported that the color, flavor, tenderness, juiciness, and overall acceptability scores of frankfurters with 1.0% NaCl + 1.0% glasswort were significantly lower than those of the control frankfurter with 1.5% NaCl. Similarly, Lim et al. (2015) noted that frankfurters with glasswort hydrate exhibited a darker color and had lower overall acceptability scores than the control.

4. Conclusion

Our findings demonstrated that partial substitution of NaCl with glasswort powder in meatball formulation can effectively improve certain physicochemical properties. The inclusion of glasswort powder increased the ash content and pH values, while decreasing the moisture content and cooking loss. These results indicate that glasswort powder contributes to enhanced cooking yield. Although instrumental color analysis revealed darker and less reddish tones in glasswort-containing samples, and sensory scores slightly decreased, particularly at higher substitution, the overall quality remained within acceptable limits according to the Turkish Uncooked Meatball Standard. Therefore, glasswort powder can be considered a promising natural ingredient for partial salt replacement in meat products, and a formulation of 0.5% NaCl and 2.0% glasswort powder, which causes minimal changes in compositional, physicochemical, and sensory properties, can be used in meatball production. However, optimization of the substitution ratio and sensory adaptation strategies is recommended for future studies to achieve a balance between technological functionality and consumer acceptability.

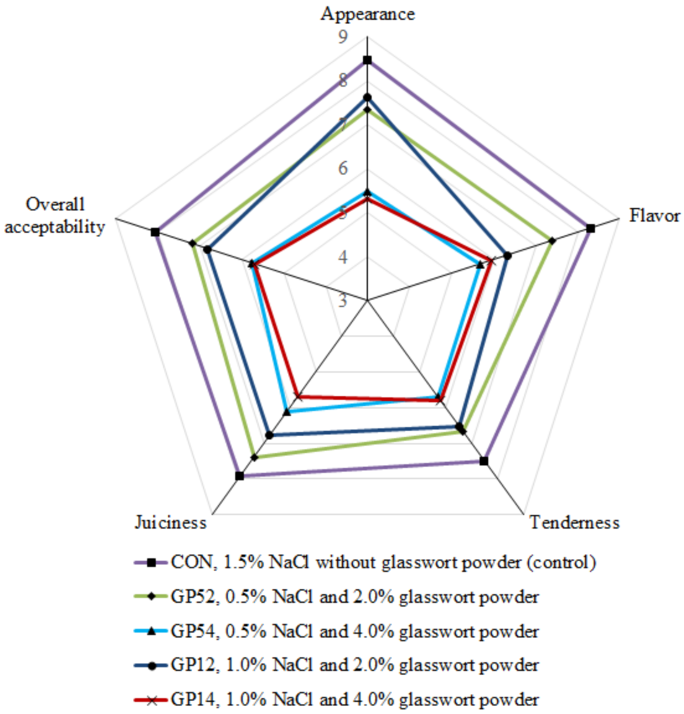

Figure 1. Sensory scores of meatballs by partially substituting NaCl with glasswort powder.

Authors' Contributions

Rümeysa Şahin: Conceptualization, Methodology, Data Analysis, Original Draft Preparation/Writing, and Theorization/Theory Development.
Sadettin Turhan: Theorization/Theory Development, Data Analysis, Methodology, Writing-Review and Editing, Visualization, Supervision.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Research and Publication Ethics Statement

The authors of this article declare that they adhere to research and publication ethics in their work.

Ethics Committee Approval Statement

The authors of this article declare that the materials and methods used in this study do not require ethical committee approval and/or any legal or special permission.

Data Availability Statement

The author declares that the data generated and analyzed during this study are available from the author upon reasonable request. No external data repository was used for this work.

Artificial Intelligence Use Statement

The authors declare that they did not use any generative artificial intelligence in the writing of this article, or in the creation of the images, graphs, tables, or their corresponding headings.

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