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Interactions of black carrot concentrate powder as a natural coloring agent with gelatine and sucrose in model gummy samples

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ABSTRACT

With growing consumer concerns about the sustainability and safety of synthetic food colorings, the food industry is increasingly turning to natural colorants derived from plants. Anthocyanins from black carrots are preferred as natural food colorants in the food industry. However, the product composition in which the colorants are used affects the pigments' color properties and stability behaviors. This study aims to determine the interaction between black carrot juice concentrate powder (BCCP) with gelatine and sucrose for model gummy samples and to develop models for the optimal composition of the product. Hardness (9.90–21.77 N), resilience (0.61–0.82), cohesiveness (0.95–0.98), springiness (0.27.5–0.63 mm), gumminess (9.63–21.30 N), and chewiness (3.15–13.36 Nxmm) properties of model gummy samples were determined by texture profile analysis. TPC values for gummy candy samples ranged from 6.87 to 44.3 mg GAE/kg, while inhibition values for AAC were 0.00%–13.4%. BCCP x gelatin and BCCP × sucrose interactions were determined to be significant for texture parameters such as hardness, gumminess, chewiness, and L*, a*, b*, and chroma values ($P < 0.05$). The optimal composition for samples was determined as 32.03 g/100 g sucrose, 21 g/100 g gelatin solution, and 0.27 g/100 g BCCP, respectively, by considering changes in hardness, springiness, hardness variation and ΔE* values at the end of accelerated shelf-life (ASL) conditions. Incorporating polyphenol-containing BCCP affects gummies' colour stability and texture.

1. Introduction

The confectionery industry is a dynamic area of food technology with high demand for and utilization of natural colorants (Kaderides et al., 2024). In 2024, the confectionery market's revenue reached USD 586.30 billion, with an anticipated annual growth rate of 5.40% (CAGR 2024–2029) (Statista, 2024). Recent years have seen an increased consumer preference for healthier and more sustainable options, driving companies to invest in research and development to create new products and reformulate existing ones to meet these demands. This trend is driven by a shift in consumer preferences towards clean-label and organic products, and a greater focus on environmental sustainability, leading companies to invest in R&D to develop new products and reformulate existing ones to meet these demands. Black carrot (BC) (*Daucus carota* ssp. *sativus var. atrorubens Alef.*), native to Turkey, the Middle East, and the Far East, exhibits blue, purple, and red hues depending on pH levels, attributed to its high anthocyanin content. Anthocyanins from BCs comprise five types of cyanidins, with at least three acylated by different aromatic acids (Ingemann Berentzen et al., 2024; Montilla et al., 2011). This acylation contributes to their notable stability, making them preferred natural food colorants due to their superior light, heat, and pH stability, positioning them as alternatives to artificial colorants (Sadilova et al., 2009). BC extracts are utilized as food colorants in fruit juices, candies, ice cream, soft beverages, and

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other fermented beverages (Hubberrmann, 2024).

Anthocyanins, responsible for coloring many plants, possess high antioxidant properties and impart bright red hues to foods. They serve as alternatives to synthetic colorants in various food applications. Beyond their coloring capabilities, anthocyanins enhance the oxidative stability of foods due to their antioxidant properties (Xiong et al., 2006). However, their low stability (Cavalcanti et al., 2011; Gérard et al., 2019) and purification challenges limit their widespread use. Factors such as pH and product matrix influence the color properties and effectiveness of various pigments. Selected colorants must maintain stability at the product's pH and exhibit desired color properties, considering potential interactions with other product components. For instance, ascorbic acid can destabilize anthocyanins (Sadilova et al., 2009), and interactions between pigments and aroma compounds can occur (Dufour & Sauvaitre, 2000). Anthocyanins are compounds with low thermal stability. Therefore, their encapsulated forms are commonly used in food applications, with maltodextrin being one of the most frequently utilized wall materials (Manzoor et al., 2021). Spray drying is commonly used method in encapsulation (Thakur & Modi, 2024). In this study, black carrot concentrate powder was used as a natural food colorant produced from maltodextrin and spray drying.

A prominent research area in food technology involves exploring interactions between polyphenols and hydrocolloids, along with their implications for technological applications and health (Lan et al., 2023; C. Li et al., 2025). Interactions between proteins, such as gelatin, and anthocyanin-rich materials like black carrot can alter techno-functional and health effects, depending on the matrices and environmental conditions involved (Raj et al., 2024). Recent studies have examined interactions between polyphenols in anthocyanin-rich food components and various hydrocolloids, noting changes in specific end-product characteristics (Sakulnarmrat & Konczak, 2022). However, studies exploring interactions between polyphenols (anthocyanins) and proteins (gelatin) in gummy candies are lacking. However, there have been no studies that explore the interactions between polyphenols (anthyanins) and proteins (gelatin) in gummy candies. Furthermore, the complexation and reactions of proteins, such as gelatin, with certain natural colorants to enhance their stability have become a focus of interest. Gelatin, a hydrocolloid protein and a major component of gummies, is critically important for achieving its unique and characteristic properties (Gunes et al., 2022). Investigating the cross-linking tendencies of polyphenols with gelatin is one of the key motivations for these studies (Lin et al., 2021).

Another group of components interacting with gelatin includes saccharides. Among these, sucrose, a major constituent of gummies, plays a crucial role. Sucrose not only promotes the formation of the gelatin network but also influences the textural properties of the product. In the presence of polyphenol-containing colorants, the interactions between gelatin and these colorants may affect both the texture and color stability of confectionery products. Additionally, the interactions and resulting products, which vary depending on the type and concentration of saccharides, can significantly influence key quality attributes, such as color and texture (Wang et al., 2024). This study investigated the impact of varying gelatin and sucrose ratios on product properties when different concentrations of concentrated black carrot powder (BCCP) were used in gummy formulations. It also aimed to determine the interactions among BCCP, sucrose, and gelatin in model gummy samples and develop models to optimize product composition.The main attributes defining confectionery products revolve around sensory and visual characteristics, aroma release, and texture properties (Gunes et al., 2022). These factors are not only individually important but also exhibit significant interdependencies. For instance, polyphenol colorants can influence the visual appeal as well as the macro- and microstructural aspects of gelatin gels (Casas-Forero et al., 2021). Moreover, the gelatin concentration and textural properties influence the perception of sweetness in gelatin-based products, such as gummy candies (Pekdogan Goztok et al., 2022). Previous studies have examined the effect of gelling agents on volatile organic compounds (VOCs) in various confectionery products as well as the release and perception of VOCs during chewing (Pizzoni et al., 2015; Saint-Eve et al., 2011). Furthermore, some studies have highlighted that increased gel hardness reduces aroma perception. Therefore, it is essential to determine the variables and conditions that influence gummy candies' textural properties and stability. For example, sugars such as sucrose and glucose cause changes in gel texture due to their effect on the water-binding properties of gelatin (Göztok et al., 2023). Furthermore, bulking agents play a role in modifying and/or improving both sensory (e.g., sweetness) and textural properties (Wang & Hartel, 2022). The novel aspect of this study lies not only in its focus on evaluating the effects of BCCP addition but also in determining the interactions among the main ingredients in gelatin-based confectionery and their impacts on key quality parameters.

2. Materials and methods

2.1. Materials

For the preparation of model gummy samples, the following ingredients were used: water, sucrose (Konya Sugar, Konya, Turkey), 40–42 DE glucose syrup (Sunar, Adana, Turkey), 220–250 bloom gelatin (Gerede Jelatin, Bolu, Turkey), and commercial encapsulated black carrot concentrate (BCCP) produced using maltodextrin as the wall material and spray drying as the encapsulation method (Sensient, Turkey). The anthocyanin content of the BCCP was determined in accordance with Commission Regulation (EU) No 231/2012, and the content was measured at 3.63%.

2.2. Study design

The study model was determined using D-Optimal mixture design method. The independent variables were the amounts of gelatin solution (220–250 Bloom, Type A, Bovine Gelatin) (15.0–20.78 g/100 g), sucrose (32.0–37.76 g/100 g), and BCCP (0.00–1.00 g/100 g). Glucose syrup (41.6 g/100 g) and water (5.10 g/100 g) contents of samples were kept constant. In addition to preparing models for the relationship and interaction between sucrose, gelatin usage and coloring agent amounts, an optimization study was conducted (Fig. 1). Hardness and springiness are the primary textural qualities that differentiate soft confectionery products and are essential for product classification. These characteristics, along with the techno-functional activities of gelatin, are directly correlated (Gunes et al., 2022b). Furthermore, the structural role of gelatin in gummies can be influenced by specific colorants, such as BCCP (Hubbermann, 2016). For these reasons, (i) texture profile analysis results (maximum hardness and springiness), (ii) ΔE^* value determined from accelerated shelf-life study (minimum), (iii) changes in hardness and springiness values determined from accelerated shelf-life study (minimum) were considered as responses at the optimization. The study design is presented in Table 1. One limitation of our study also needs to be considered. Gelatin must be used as a gelatin solution in gummy production (gelatin: water, 1:3). Additionally, this solution should be added to the main mixture after heat treatment (Hartel et al., 2018). Consequently, in studies where the gelatin solution is a variable, the initial total water content may vary with each trial. In our study, the water content in the formulations was kept constant (5.10 g/100 g). However, depending on the amount of gelatin solution used (15.0–20.78 g/100 g), there was a variation in the amount of total water used to prepare the samples (15.46–19.47 g/100 g). As in our previous study, the heat treatment solution was applied to minimize this potential effect until a specific total soluble solids (TSS) value (85.0 °Bx) was reached before adding the gelatin solution (Dalabasmaz et al., 2024).

2.3. Sample preparation

Water, sucrose, 42 DE glucose syrup, gelatin solution and natural

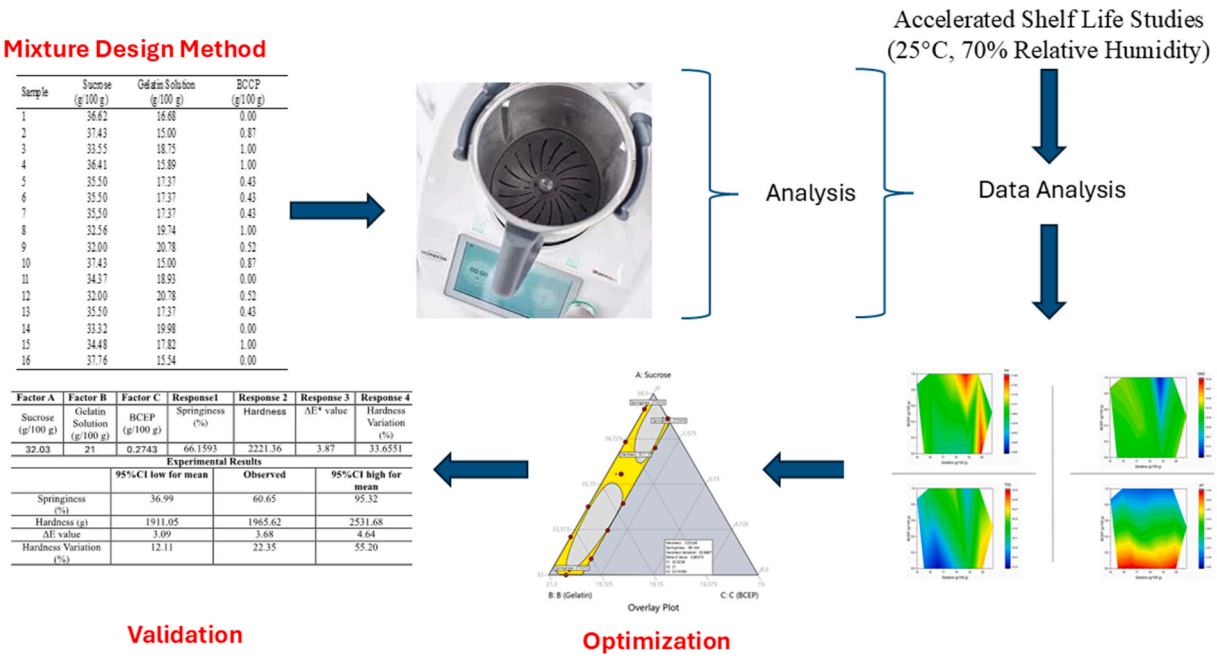

Fig. 1. Sensorial evaluation of BCEP-added and not-added gummies at the optimum point indicates insignificant differences ($P > 0.05$) according to the Independent *t*-test.

coloring (BCCP) were used to prepare the gummy candy samples. Water, sucrose and glucose syrup were mixed in a thermal mixer (Thermomix TM5, Vorwerk, Germany) and heated to 100 °C. This temperature was maintained for approximately 10 min to obtain a solution with 85.0 ± 1.00°Bx (under 200–300 rpm agitation). The samples were then cooled to 90.0 °C. A pre-prepared 250-bloom gelatin:water solution (1:3) was added to the samples and stirred at 90.0 ± 2.00 °C for 2 min at 200–300 rpm. Next, BCCP was added to the samples, which were then rapidly cooled to 60.0 ± 1.00 °C, followed by additional stirring for 1 min at 200–300 rpm. After the specified time, the mass was transferred to silicone molds and allowed to stand at 20 °C for 24 h. The demolded samples were coated with starch to prevent sticking and placed in polyethylene bags for storage at room temperature. The experiments were carried out in batches of approximately 500 g each. Samples with the optimal gummy component were identifed, and a control sample was prepared for sensory evaluation. To prepare the control sample, previous formulations without any coloring agents were used as a reference (Dalabasmaz et al., 2024).

2.4. Physico-chemical analysis

The dry matter content of the samples was determined using the gravimetric technique (Periche et al., 2015). Water activity values were determined using a water activity analyzer (Water Lab, Steroglass, Umbria, Italy). pH values were determined using a pH meter (Ohaus, AquaSearcher, AB33 pH Bench Meter, NJ, USA). Total amounts of soluble solids were determined using a refractometer (Abba, Atago, Tokyo, Japan). Each measurement was performed in triplicate.

2.5. Texture analysis

The model gummy samples, with a diameter of 28 mm and a height of 20 mm, were subjected to Texture Profile Analysis (TPA) using a TX-XT plus instrument (Stable Micro Systems, Godalming, UK). The device has a 5 kg load cell and a 35 mm diameter cylindrical probe. A 50% compression was applied twice consecutively, with an interval of 15 s between compressions. The test speed was set at one mm/s. Five replicates were performed for each sample (Gok et al., 2020).

2.6. Antioxidant activity capacity and total phenolic content analysis

2.6.1. Antioxidant activity capacity

The DPPH antioxidant capacity was determined using the DPPH method described by Brand-Williams et al. (1995). To prepare the sample solution, 20 mL of 80% methanol solution was added to 2 g sample and stirred for 1 h. After centrifugation at 3000*g* and 25 °C for 15 min, 100 μL of the supernatant from the samples was reacted with 3.5 mL of the DPPH solution for 30 min in the dark. Absorbances were then measured at 517 nm using a UV spectrophotometer (Jasco, Japan). The antioxidant activity capacity of samples was determined using % inhibition values in Eq. (1).

$$\%\ Inhibition = [(A_C - A_T) / A_C]\ x\ 100 \quad (1)$$

Ac; Control absorbance value, At; sample absorbance value.

2.6.2. Total phenolic content

The total phenolic content of gummy samples was determined according to the method used by Cao et al. (2011). A 40 μL sample diluted with methanol was placed in a spectrophotometer cuvette, followed by the addition of 3.16 mL of pure water and 200 μL of Folin-Ciocalteu reagent solution (Merck, Darmstadt, Germany). After waiting 1–2 min, 600 μL of 20% sodium carbonate (Merck, Germany) solution was added. The mixture was then left at room temperature for 2 h, after which the absorbance values were read at 765 nm wavelength against a blank using a spectrophotometer (UV 1240, Shimadzu, Kyoto, Japan). The calculation was performed using a gallic acid calibration curve. Analysis was performed in triplicate.

2.7. Color analysis

The color properties of gummy samples were examined using the CIE-Lab method (L*, a*, b*, C*, and h°) with a colorimeter (CR-4000, Konica Minolta, Japan). The L* (luminance), a* (±red-green) and b* (±yellow-blue) values of the samples were measured and the chroma (C*), hue angle (h°) and total color difference (ΔE) values were calculated by using Eqs. (2)–(4). Analyses were carried out in five replicates.

Table 1
Physico-chemical color and bioactive properties of gummy candy samples including BCCP.

Run	Sucrose[a]	Gelatin Solution[a]	BCCP[a]	TSS (°Bx)	DMC (g/100 g)	Water Activity	pH	L[a]	a[a]	b[a]	C[a]	Hue Angle	TPC (mg GAE/kg)	AAC (%, Inhibition)
1	36.62	16.68	0.00	85.9 ± 0.01^{f}	82.6 ± 0.44^{a}	0.70 ± 0.03^{abc}	5.41 ± 0.01^{c}	95.2 ± 0.20^{a}	−0.82 ± 0.06^{g}	5.12 ± 0.09^{d}	5.18 ± 0.09^{j}	99.1 ± 0.71^{i}	6.87 ± 0.01^{f}	0.00 ± 0.01^{h}
2	37.43	15.00	0.87	88.0 ± 0.01^{c}	82.8 ± 0.19^{a}	0.70 ± 0.01^{abc}	4.71 ± 0.01^{h}	44.6 ± 1.25^{gh}	25.7 ± 0.53^{ab}	−6.38 ± 0.04^{hi}	27.0 ± 0.52^{a}	346.3 ± 0.28^{cd}	30.0 ± 0.02^{cd}	6.86 ± 0.06^{cd}
3	33.55	18.75	1.00	87.7 ± 0.01c	80.0 ± 0.29^{bcd}	0.71 ± 0.01^{abc}	4.87 ± 0.02^{g}	36.8 ± 0.69^{i}	24.5 ± 0.31^{abc}	−4.50 ± 0.21^{e}	24.9 ± 0.3^{abc}	349.6 ± 0.36^{a}	44.3 ± 0.09^{a}	11.4 ± 0.01^{ab}
4	36.41	15.89	1.00	89.4 ± 0.01^{b}	81.7 ± 0.56^{ab}	0.67 ± 0.01^{bc}	4.76 ± 0.02^{h}	51.0 ± 0.54^{ef}	24.7 ± 1.07^{abc}	−6.51 ± 0.15^{hi}	25.6 ± 1.04^{abc}	345.3 ± 0.33^{de}	39.4 ± 0.06^{ab}	10.1 ± 0.02^{bc}
5	35.50	17.37	0.43	86.6 ± 0.01^{a}	81.4 ± 0.44^{abc}	0.65 ± 0.01^{c}	5.09 ± 0.02^{f}	52.5 ± 1.66^{e}	22.4 ± 0.76^{cd}	−7.26 ± 0.10^{jk}	23.6 ± 0.73^{cd}	342.1 ± 0.53^{f}	22.8 ± 0.02^{e}	4.97 ± 0.05^{ef}
6	35.50	17.37	0.43	85.0 ± 0.01^{g}	80.3 ± 0.35^{bcd}	0.68 ± 0.00^{abc}	5.19 ± 0.03^{de}	51.8 ± 1.07^{ef}	22.8 ± 0.40^{cd}	−7.45 ± 0.07^{k}	24.0 ± 0.40^{cd}	341.9 ± 0.16^{f}	23.7 ± 0.03^{de}	4.55 ± 0.07^{f}
7	35,50	17.37	0.43	84.1 ± 0.01^{i}	81.0 ± 0.14^{abc}	0.71 ± 0.01^{abc}	5.23 ± 0.03^{d}	52.6 ± 0.00^{c}	24.7 ± 0.00^{abc}	−6.14 ± 0.00^{h}	25.9 ± 0.00^{abc}	337.2 ± 0.00^{h}	24.8 ± 0.05^{de}	4.70 ± 0.03^{ef}
8	32.56	19.74	1.00	85.4 ± 0.01^{g}	79.9 ± 0.39^{cd}	0.75 ± 0.02^{a}	5.06 ± 0.01^{f}	44.5 ± 1.94^{gh}	20.9 ± 1.67^{d}	−5.09 ± 0.45^{ef}	21.5 ± 1.73^{de}	346.3 ± 0.09^{cd}	36.8 ± 0.04^{bc}	10.4 ± 0.01^{bc}
9	32.00	20.78	0.52	89.2 ± 0.01^{a}	80.3 ± 0.13^{bcd}	0.71 ± 0.03^{abc}	5.23 ± 0.02^{d}	61.0 ± 1.55^{d}	17.2 ± 1.09^{e}	−6.36 ± 0.42^{hi}	18.3 ± 1.16^{fg}	339.8 ± 0.07^{g}	29.6 ± 0.03^{cd}	3.23 ± 0.06^{g}
10	37.43	15.00	0.87	87.4 ± 0.01^{d}	82.8 ± 0.21^{a}	0.66 ± 0.03^{c}	4.92 ± 0.02^{g}	43.0 ± 1.17^{h}	26.5 ± 0.32^{a}	−5.96 ± 0.17^{gh}	27.2 ± 0.29^{a}	347.3 ± 0.49^{bc}	35.0 ± 0.01^{bc}	10.7 ± 0.05^{bc}
11	34.37	18.93	0.00	86.7 ± 0.01^{e}	81.4 ± 0.31^{abc}	0.74 ± 0.01^{ab}	5.64 ± 0.02^{b}	86.8 ± 0.76^{b}	−1.11 ± 0.02^{g}	6.33 ± 0.28^{b}	6.43 ± 0.27^{ij}	100.0 ± 0.43^{i}	7.95 ± 0.02^{f}	0.00 ± 0.09^{h}
12	32.00	20.78	0.52	86.5 ± 0.01^{e}	80.0 ± 0.18^{bc}d	0.74 ± 0.02^{ab}	5.20 ± 0.02^{d}	64.1 ± 1.83^{d}	18.3 ± 1.37^{e}	−6.90 ± 0.41^{ijk}	19.6 ± 1.43^{ef}	339.3 ± 0.30^{g}	19.3 ± 0.05^{ef}	5.43 ± 0.04^{d}
13	35.50	17.37	0.43	86.1 ± 0.01^{f}	81.6 ± 0.46^{abc}	0.72 ± 0.01^{abc}	5.40 ± 0.01^{c}	47.6 ± 1.15^{fg}	23.3 ± 0.53^{bcd}	−6.61 ± 0.04^{hij}	24.2 ± 0.50^{bc}	344.2 ± 0.43^{e}	25.1 ± 0.03^{de}	6.01 ± 0.02^{d}
14	33.32	19.98	0.00	85.4 ± 0.01^{g}	78.8 ± 0.12^{d}	0.72 ± 0.04^{abc}	5.74 ± 0.01^{a}	44.7 ± 1.32^{gh}	−0.89 ± 0.07^{g}	10.5 ± 0.18^{a}	10.5 ± 0.18^{h}	94.9 ± 0.38^{j}	6.41 ± 0.02^{f}	0.00 ± 0.01^{h}
15	34.48	17.82	1.00	84.6 ± 0.01^{h}	81.2 ± 0.23^{abc}	0.74 ± 0.01^{ab}	5.13 ± 0.02^{ef}	41.8 ± 1.20^{h}	26.2 ± 0.47^{a}	−5.29 ± 0.06^{fg}	26.7 ± 0.44^{ab}	348.6 ± 0.32^{ab}	39.1 ± 0.03^{ab}	13.4 ± 0.02^{a}
16	37.76	15.54	0.00	87.4 ± 0.01^{d}	82.8 ± 0.06^{a}	0.72 ± 0.03^{abc}	5.74 ± 0.01^{a}	90.9 ± 0.19^{b}	−1.01 ± 0.01^{g}	5.77 ± 0.04^{bc}	5.90 ± 0.11^{hi}	99.7 ± 0.24^{i}	7.04 ± 0.02^{f}	0.00 ± 0.01^{h}

[a] g/100 g; Mean ± Standard deviation; C*; Chroma, BCEP; Black Carrot Concentrate Powder; TSS; Total Soluble Solids, DMC; Dry Mater Content, TPC; Total Phenolics Content; AAC; Antioxidant Activity Capacity. The same superscript lowercase letters in each column indicate no significant differences ($P < 0.05$).

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

$$h^* = \arctan\left(b^* / a^*\right) \quad (3)$$

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (4)$$

2.8. Accelerated shelf life study

After preparation, the samples were placed in a shelf-life cabinet without packaging and accelerated shelf-life testing conditions were applied at 25 °C and 70% RH, according to the method described by Subramaniam (2016). Color (Section 2.7) and texture profile analysis (Section 2.5) were conducted at 7-day intervals. L* (brightness), a* (±red-green), and b* (±yellow-blue) values were measured, and ΔE* values were determined based on Eq. (4). Five replicates were performed for each color and TPA analysis. ΔL*, Δa*, and Δb* values were calculated based on the initial measurements. Additionally, the difference between the TPA measurements at the beginning and after 63 days of total storage at 25 °C and 70% RH was calculated as a percentage change (%). Five replicates were performed for each color and TPA analysis.

2.9. FTIR analysis

Spectral measurements were performed within the range of 4000–500 cm^{-1}. All measurements were performed in triplicate with a diamond triple-bounce ATR accessory (Bruker Alpha, Germany)

2.10. Sensory analysis

Gummy samples with a composition determined based on the results of characterization and accelerated shelf-life studies were prepared. The sensory characteristics of the control (without BCCP) and optimum gummy sample were determined by 40 untrained graduate students from the Food Engineering Department at Eskişehir Osmangazi University. Sensory properties, including appearance, taste, elasticity, structure, and general acceptability, were assessed using a hedonic scale (9: the best, 1: the worst score)

2.11. Statistical analysis

The results of the analyses were expressed as mean ± standard deviation. Data obtained from the shelf-life studies were subjected to one-way analysis of variance (ANOVA), and Tukey's test was applied for comparisons ($P < 0.05$). All statistical analyses were conducted using Minitab version 13.0 (Chicago, IL, USA).

For the mixture design results, ANOVA was performed to assess the statistical significance of the outcomes. Multiple linear regression was employed to identify the most suitable models for the analysis results. Regression coefficients of the most appropriate models, as well as interaction terms among linear, quadratic, and cubic models, were determined. Lack of fit, regression, and p-values were used to validate the models and evaluate the effects of independent variables on gummy samples. For a model to be deemed significant, the lack of fit must not be significant.

The p-value associated with the selected model was used to examine the significance of each parameter in the equation. A p-value less than 0.05 indicates that the model terms are significant. When a factor has a p-value smaller than 0.05, it significantly influences the independent variable(s) at a confidence level of 0.95. Conversely, if the p-value exceeds 0.05, the likelihood of other coefficients being present in the equation is greater than 95%, suggesting that the parameter in question is not significant (Pour Hosseini et al., 2017).

To validate the models, experimental and predicted values were compared. The results demonstrated consistency within the 95% prediction intervals.

3. Results and discussion

3.1. Physico-chemical properties

In this study, the total soluble solids (TSS) content of the model gummy syrups prepared during sample preparation was investigated and the effects of independent variables were modeled significantly ($P < 0.05$) (Supplementary File 1). The linear effects of each independent variable were found to be significant, however, the R^2 value for this model was relatively low (0.4219). The water activity values of confectionery products typically range between 0.500 and 0.850 depending on the product's type, production technology, and composition (Hartel et al., 2018). Due to their low water activity, gummies provide a favourable environmental conditions for the stability of anthocyanin colorants (Hubbermann, 2024). In this study, the water activity values of model gummy samples ranged between 0.65 and 0.74 (Table 1) aligning with the values of previous studies. Although these awaw values exceed the safe threshold of 0.600 (Fan et al., 2017; Kowalski et al., 2017), it is important to note that modifications aimed at achieving lower awaw values may negatively impact the quality characteristics of gummies, particularly their texture. Furthermore, there is a strong interaction between the aw values and the production technology and composition of confectionery products. Water activity is also closely associated with various stability behaviors of gummy candies (Ergun et al., 2010). Therefore, interactions with other quality attributes should be considered. A significant model was not determined for this parameter ($P < 0.05$) (Supplementary File 1). However, the amounts of sucrose and gelatin solution had positive and negative mild correlations with water activity, respectively (Table 2). Sugars are known to influence the water activity within gel structures (Su et al., 2021). The presence of sugars generally decreases water activity and increases the gel structure's stability leading to higher melting temperatures and enthalpies (Hartel et al., 2018). The sugar profile and concentration are closely related to these effects (Göztok et al., 2023). For example, an increase in reducing sugar content can lead to a decrease in water activity.

Furthermore, the correlation constants of water activity with dry matter content (DMC) (−0.635) and L* value (−0.520) were found to be noteworthy. The properties of gel structures are significantly influenced by the hydrocolloid gelling agent used and the moisture content in the final product. As a result, regulating moisture levels during confectionery production is essential for controlling gel formation behavior and ensuring heat stability (Wang & Hartel, 2022). This correlation also extends to the characteristic behaviors exhibited by the final product. Additionally, the covalent bonding of flavan-3-ols with gelatin and other proteins has been shown to increase the water-holding capacity of gel structures (Li et al., 2025). Similar interactions have been observed between gluten and polyphenols (Hu et al., 2024) which could potentially affect water activity. However, the results of these possible interactions were not observed in this study.

The DMCs of the samples in this study ranged from 78.8 to 82.8 g/100 g (Table 1), all exceeding the critical lower limit of 76.0 g/100 g defined for the product group concerned (Hartel et al., 2018). A significant model regarding the effects of independent variables on this parameter was not determined ($P < 0.05$). This can be considered a disadvantage, as DMC is critically important due to its impact on the primary quality characteristics of confectionery products (Ergun et al., 2010; Hartel et al., 2018). Interactions between moisture content and gelatin influence texture (Dalabasmaz et al., 2024; Wang & Hartel, 2022). Furthermore, there is a significant relationship between the sugar profile of confectionery products and moisture content (Ergun et al., 2010). However, in our study, no significant relationship was identified between DMC and the components listed as independent variables, which influence the final product's sugar profile.

Factors such as cooking temperature, sugar composition, and

Table 2
Correlation coefficients (r) between variables.

	A : Sucrose	B : GelatinSolution	C : ColoringAgent	Hardness	Resilience	Cohesiveness	Springiness	Gumminess	Chewiness	TTS	DMC	aw	pH	L*	a*	b*	C*	HueAngle	HardnessVariance	ΔE	TPC	AAP
A:Sucrose	1.000																					
B:Gelatin Solution	−0.979	1.000																				
C:Coloring Agent	−0.089	−0.115	1.000																			
Hardness	−0.787	0.840	−0.271	1.000																		
Resilence	−0.647	0.643	0.011	0.555	1.000																	
Cohesiveness	−0.585	0.582	0.008	0.408	0.054	1.000																
Springiness	−0.113	0.118	−0.028	0.266	0.199	0.251	1.000															
Gumminess	−0.798	0.849	−0.264	0.999	0.574	0.442	0.273	1.000														
Chewiness	−0.533	0.571	−0.195	0.793	0.458	0.374	0.786	0.795	1.000													
TTS	−0.649	0.632	0.078	0.649	0.233	0.462	0.232	0.659	0.533	1.000												
DMC	0.180	−0.138	−0.204	−0.105	−0.594	−0.124	0.350	−0.109	0.118	0.328	1.000											
aw	−0.197	0.168	0.141	0.312	0.419	−0.005	−0.066	0.305	0.230	−0.054	−0.635	1.000										
pH	0.091	0.106	−0.965	0.319	0.048	−0.039	0.014	0.309	0.231	−0.091	0.038	−0.035	1.000									
L*	0.219	−0.066	−0.746	−0.070	−0.219	−0.142	−0.164	−0.075	−0.172	−0.255	0.180	−0.520	0.748	1.000								
a*	−0.013	−0.167	0.881	−0.411	−0.050	0.017	−0.149	−0.402	−0.359	0.034	−0.063	0.081	−0.930	−0.775	1.000							
b*	0.064	0.087	−0.739	0.441	0.098	−0.026	0.228	0.432	0.444	−0.054	−0.043	0.183	0.819	0.533	−0.924	1.000						
C*	−0.001	−0.176	0.868	−0.380	−0.028	0.011	−0.098	−0.352	−0.283	0.063	−0.068	0.185	−0.910	−0.854	0.985	−0.857	1.000					
Hue Angle	−0.153	−0.016	0.827	−0.311	−0.026	0.079	−0.149	−0.301	−0.306	0.147	−0.004	−0.054	−0.890	−0.688	0.962	0.974	0.918	1.000				
Hardness Variance	−0.177	0.119	0.283	0.043	0.527	0.315	0.309	0.057	0.239	0.071	−0.222	0.381	−0.328	−0.615	0.409	−0.278	0.486	0.348	1.000			
ΔE	0.121	−0.135	0.072	−0.291	−0.069	−0.214	−0.174	−0.293	−0.296	−0.251	−0.178	−0.327	0.004	0.325	−0.033	−0.072	−0.073	−0.022	−0.049	1.000		
TPC	−0.119	−0.079	0.969	−0.241	0.046	0.049	−0.082	−0.233	−0.221	0.123	−0.182	0.125	−0.953	−0.741	0.888	−0.768	0.865	0.8555	0.274	−0.093	1.000	
AAP	−0.061	−0.135	0.959	−0.296	−0.049	0.035	−0.046	−0.288	−0.219	0.026	−0.151	0.202	−0.956	−0.753	0.857	−0.676	0.855	0.772	0.271	−0.050	0.937	1.000

TTS; Total Soluble Solids, DMC; Dry Matter Content, aw; Water Activity, TPC; Total Phenolics Content; AAP; Antioxidant Activity Potential; C*; Chroma. $r < 0.30$; no correlation or weak correlation, $0.30 < r < 0.50$; weak correlation $0.50 < r < 0.70$; mild correlation, $r > 0.70$; strong correlation.

changes resulting from potential sugar inversion have been reported to increase gelatin-based gel food products' moisture content thereby decreasing DMC. It is also important to consider gelatine hydrolysis, which can occur depending on the processing conditions. A certain level of gelatin hydrolysis can enhance gel formation capacity and the ideal degree of hydrolysis depends on the moisture content (Wang & Hartel, 2022). However, a reduction in this capacity may occur due to cross-linking of gelatin, potentially leading to an increase in DMC.

The typical pH of gummies, which includes food acids, especially citric acid, ranges from 3.00 to 5.00 (Burey et al., 2009; Wang & Hartel, 2022). For example, Ge et al. (2021) reported this value as 3.15–5.00. Whereas Wang and Hartel (2022) determined this value to be 5.00–5.30 for samples without food acid. Citric acid is commonly used in some gummy formulations (Hartel et al., 2018) to enhance flavor perception and modify certain textural properties (Wang & Hartel, 2022). However, citric acid was not used in our study for two reasons. Firstly, changes in textural properties due to the presence of citric acid were considered, as well as its potential effect in promoting sucrose inversion one of the independent variables in our study.

The pH values should be considered when evaluating the coloring effect and stability of the coloring agents. In this study, the pH values of the samples were determined to be in the range of 4.71–5.74 (Table 1). These relatively high pH values observed during the sample preparation process can be attributed to the absence of citric acid. For example, Ge et al. (2021) reported a pH range of 3.15–5.00 for such samples. In contrast, Wang and Hartel (2022) found that samples without food acids had a higher pH range of 5.00–5.30. A significant linear model was chosen for the effect of independent variables on the pH values of the samples ($P < 0.05$) (Supplementary File 3). According to this model, all independent variables significantly affect the pH values of gummy candies, but the primary influential independent variable is the BCCP content. The use of BCCP leads to a decrease in pH value; when combined with sucrose, this component causes lower pH values. Farhan et al. (2024) found that pH values decreased from 4.3 to 4.0 when the beetroot powder concentration supplementation levels increased from 2 to 10 % hard candies. The gradual decrease in pH may be linked to acid formation, degradation of polysaccharides, oxidation of reducing sugars and low pH values. The concentration of gelatine solution has a pH-increasing effect (Supplementary File 3). The use of materials with different hygroscopic properties can affect the pH values of foods due to their buffering capacity, impact on moisture content, and effects on solubility and ionic balance. The study also examined the interactions between changes in the amounts of these anthocyanins and other quality parameters (Table 2). The strong correlation between pH and BCCP (0.889) and colour parameters such as a* (−0.856), b* (0.778), chroma (−0.834) and hue angle (−0.806) was in agreement with previous studies. Negative correlations between pH and total phenolic content (TPC) (−0.953) and antioxidant activity capacity (AAC) (−0.956) indicate that the use of high amounts of BCCP may lead to increases in TPC and AAC in the final product.

3.2. Texture

Hardness (9.90–21.77 N), resilience (0.61–0.82), cohesiveness (0.95–0.98), springiness (0.27.5–0.63 mm), gumminess (9.63–21.30 N), and chewiness (3.15–13.36 Nxmm) properties of model gummy samples were determined through texture profile analysis (Table 3). Except for springiness and cohesiveness, significant linear and quadratic models were identified for TPA parameters (Supplementary File 2) ($P < 0.05$). The R^2 values for these models were 0.5715–0.9908, and the interactions between sucrose x gelatin solution, sucrose x BCCP, and gelatin solution x BCCP, as well as the individual effects of the independent variables were determined as significant for various texture properties (Supplementary File 2). Gelatin serves multifunctional roles as a gelling agent, texturizer, and water binder, making it a fundamental component in soft confectionery products and the most preferred hydrocolloid (Hartel et al., 2018). These products are essentially biopolymer gel systems containing sugars formed in an aqueous medium (Gunes et al., 2022b). The sugar composition and concentrations profoundly influence their macro- and micro-structural properties (Casas-Forero et al., 2022). The incorporation of sugars increases gelatin network strength through attractive forces between them as well as repulsion from the sugar phase (Amjadi et al., 2018; Cebi et al., 2019). Periche et al. (2015) observed significant effects on texture parameters like hardness and chewiness when altering gelatine amounts in formulations, noting that sugars and their combinations further influence these mechanical properties. The effects of these variables (sugars and gelatin) on adhesion and springiness, whether combined or separate, have been determined at lower densities (Supplementary File 6). However, significant efforts are being made to reduce or replace sugar, gelatine, artificial sweeteners and colouring with natural alternatives to reflect evolving consumer preferences and demands (Konar et al., 2022). Consequently, it is important to investigate the changes in gelatine concentration under different processing conditions. In particular, an increase in gelatine concentration coincides with a simultaneous increase in gel hardness (Aidat et al., 2023). This is because hardness is a textural parameter also considered in the classification of confectionery products. It has been determined that factors such as the type and level of hydrocolloids, various processing conditions, and composition influence hardness (Dalabasmaz et al., 2024; Wang et al., 2024). Changes

Table 3
Texture properties of gummy candy samples including BCCP.

Sample	Sucrose[a]	Gelatin Solution[a]	BCCP[a]	Hardness (N)	Resilence	Cohesiveness	Springiness (mm)	Gumminess (N)	Chewiness (Nxmm)
1	36.62	16.68	0.00	$11.12 + 0.11^{ghi}$	$0.71 + 0.02^{bcdef}$	$0.98 + 0.02^{a}$	$0.52 + 0.06^{a}$	$10.85 + 0.31^{fg}$	$5.59 + 0.45^{ab}$
2	37.43	15.00	0.87	$10.60 + 0.47^{i}$	$0.72 + 0.04^{abcdef}$	$0.97 + 0.01^{a}$	$0.36 + 0.04^{a}$	$10.24 + 0.35^{g}$	$3.73 + 0.44^{b}$
3	33.55	18.75	1.00	$14.96 + 0.35^{c}$	$0.83 + 0.01^{a}$	$0.98 + 0.01^{a}$	$0.34 + 0.02^{a}$	$14.69 + 0.17^{cd}$	$5.06 + 0.17^{b}$
4	36.41	15.89	1.00	$10.56 + 0.55^{cd}$	$0.65 + 0.07^{def}$	$0.95 + 0.04^{a}$	$0.41 + 0.06^{a}$	$10.04 + 0.93^{g}$	$4.13 + 0.28^{b}$
5	35.50	17.37	0.43	$11.48 + 0.79^{efg}$	$0.74 + 0.03^{abcde}$	$0.98 + 0.01^{a}$	$0.39 + 0.01^{a}$	$11.23 + 0.67^{efg}$	$4.38 + 0.21^{b}$
6	35.50	17.37	0.43	$10.98 + 0.57^{a}$	$0.76 + 0.02^{abcd}$	$0.99 + 0.01^{a}$	$0.45 + 0.03^{a}$	$10.83 + 0.67^{fg}$	$4.87 + 0.13^{b}$
7	35,50	17.37	0.43	$13.40 + 0.55^{ef}$	$0.64 + 0.03^{ef}$	$0.98 + 0.01^{a}$	$0.44 + 0.02^{a}$	$13.09 + 0.47^{de}$	$5.73 + 0.18^{ab}$
8	32.56	19.74	1.00	$16.26 + 0.83^{efgh}$	$0.8 + 0.03^{ab}$	$0.98 + 0.01^{a}$	$0.61 + 0.31^{a}$	$15.95 + 0.91^{bc}$	$9.94 + 5.63^{ab}$
9	32.00	20.78	0.52	$18.02 + 0.73^{hi}$	$0.77 + 0.03^{abc}$	$0.98 + 0.01^{a}$	$0.38 + 0.01^{a}$	$17.7 + 0.73^{b}$	$6.74 + 0.22^{ab}$
10	37.43	15.00	0.87	$9.91 + 0.18^{cd}$	$0.63 + 0.02^{ef}$	$0.97 + 0.01^{a}$	$0.59 + 0.29^{a}$	$9.63 + 0.3^{g}$	$5.77 + 3.04^{ab}$
11	34.37	18.93	0.00	$16.10 + 0.43^{hi}$	$0.8 + 0.01^{ab}$	$0.99 + 0.01^{a}$	$0.37 + 0.03^{a}$	$15.86 + 0.39^{bc}$	$5.88 + 0.50^{ab}$
12	32.00	20.78	0.52	$15.01 + 0.71^{fghi}$	$0.71 + 0.02^{bcdef}$	$0.98 + 0.02^{a}$	$0.37 + 0.02^{a}$	$14.65 + 0.72^{cd}$	$5.37 + 0.17^{ab}$
13	35.50	17.37	0.43	$12.92 + 0.13^{hi}$	$0.68 + 0.0^{1cdef}$	$0.96 + 0.02^{a}$	$0.3 + 0.03^{a}$	$12.38 + 0.19^{ef}$	$3.76 + 0.43^{b}$
14	33.32	19.98	0.00	$21.77 + 0.61^{de}$	$0.77 + 0.05^{abc}$	$0.98 + 0.01^{a}$	$0.63 + 0.09^{a}$	$21.3 + 0.61^{a}$	$13.36 + 0.10^{a}$
15	34.48	17.82	1.00	$12.99 + 0.84^{bc}$	$0.67 + 0.04^{cdef}$	$0.99 + 0.01^{a}$	$0.29 + 0.02^{a}$	$12.81 + 0.75^{de}$	$3.74 + 0.09^{b}$
16	37.76	15.54	0.00	$12.05 + 0.32^{b}$	$0.61 + 0.05^{f}$	$0.95 + 0.05^{a}$	$0.28 + 0.01^{a}$	$11.45 + 0.27^{efg}$	$3.15 + 0.10^{b}$

[a] g/100 g, Mean ± standard deviation, BCCP; Black Carrot Concentrate Powder. The same superscript lowercase letters in each column indicate no significant differences ($P < 0.05$).

affecting the structure formed by hydrocolloids in the product composition result in gummy candies and gel structures with varying hardness characteristics (Aidat et al., 2023). In this study, the increase in the amount of gelatine solution had a similar effect and showed a positive and strong correlation with the hardness values (r = 0.840). Whereas the amount of sucrose showed a strong negative correlation. Furthermore, the interactions between gelatine solution, sucrose, and BCCP concentrations, as well as the interactions between sucrose and BCCP a, were determined as significant for model gummy hardness ($P < 0.05$) (Supplementary File 7). A recent study reported that the covalent bonding of gelatin and some other proteins with epigallocatechin gallate resulted in increased gel strength and the formation of a dense structure (Li et al., 2025). Previous studies have particularly linked gummy hardness with gelatine quantity, bloom degree, adding temperature, and other environmental conditions. For confectionery products, gelatine is typically added to the mixture or sugar syrups at temperatures around 60 °C (Hartel et al., 2018). In continuous systems for confectionery production lines, this temperature can rise to 90–95 °C. However, when considering higher gelatine addition temperatures (>60 °C), it is important to consider the pH and acidity of the product (Wang & Hartel, 2022). For instance, when pH values are close to 5, the loss in the degree of gelatine bloom is approximately 10% at 90 °C for 30 min (Hartel et al., 2018). Environmental conditions and mechanical factors during processing may also affect the textural properties of the final product, and it would be useful to investigate these effects on the stability of colorants such as BCCP. The study revealed that BCCP concentration and its interactions with other main components significantly affect hardness. The increase in hardness in viscoelastic jelly-like confectionery products leads to forming a three-dimensional network that traps volatile compounds tightly in the matrix and prevents mass transfer (Pizzoni et al., 2015). These findings may be valuable for developing products tailored to various consumer groups and their demands. Previous studies have emphasized the effects of gummy composition on mechanical properties (Xie et al., 2023). In addition to the gelatine concentration, sugars also play a role in stabilizing gummies. The gelatine network in water contributes to greater gel rigidity (Ge et al., 2021). Wang and Hartel (2022) emphasized that the adhesion and cohesion forces of gelatine-based candies can be affected by gelatine concentration. However, in this study, the amount of gelatine solution had no significant effect on cohesiveness ($P < 0.05$). The decrease in cross-linking between gelatine molecules may result in a decrease in adhesion values (Amjadi et al., 2018).

The effects of other independent variables on cohesiveness and springiness were insignificant ($P < 0.05$). In gummies, the interactions between sugars and hydrocolloids may affect texture properties such as cohesion over time, while compositional changes that lead to increased acidity and pH also influence textural attributes (do Nascimento et al., 2023). In general, changes in gummy cohesiveness occur due to increased shear forces with temperature effects on these bonds. Gummies typically exhibit adhesive properties, which can pose challenges for processing and packaging lines (Wang & Hartel, 2022). Gumminess and chewiness are textural parameters that generally follow a similar trend to hardness and gel strength (Zhao et al., 2021). Therefore, factors affecting hardness are also expected to cause changes in these properties. Similar mechanisms also apply to chewiness and gumminess. In this study, a significant model was determined for the effects of the independent variables on gumminess and a strong correlation was found between these two parameters (Table 2). The effects of gelatine on binding behavior and mechanism, considering the sugar profile, gelling agent composition, junctions, water-binding properties, and interactions between gelatine molecules, have been investigated, and it was determined that they also affect springiness behaviors have been investigated. However, no study was found on the effect of the amount of colorant on springiness behavior. This study also determined that the interaction of BCCP with other independent variables significantly affected the gumminess, resilience, and chewiness properties of gummies ($P < 0.05$).

3.3. Color

Thermal processing was applied during the preparation of gummy samples. Anthocyanins may undergo degradation during this process, as the pigments are highly sensitive to heat and oxidation. Under these environmental conditions, isomerization and decarboxylation reactions typically occur (Herbach et al., 2006). In general, the effects of thermal processing in the production of gelatin-containing gummy candies have been found to cause a decrease in L* values and increases in a* and b* values (Wang & Hartel, 2022). Therefore, determining the relationship between our independent variables and color properties is essential. Additionally, in this study, the pigment source was also among the variables considered. The main color characteristics (L*, a*, b*, chroma, and hue angle) of model gummy samples and their relationships with sucrose, BCCP, and gelatine solution concentrations were investigated (Table 1). The L*, a*, b*, chroma, and hue angle values were determined as 44.5–95.2, (−1.11)-26.2, (−7.45)-10.5, 5.18–27.2, and 94.9–349.6, respectively. Significant quadratic models were determined for all color parameters, and the R^2 values of these models ranged from 0.9064 to 0.9999 (Supplementary File 3). The interactions of sucrose x gelatine solution were found not to be significant in the other color parameters except the L* value (Supplementary File 6). Therefore, the interactions between the amount of BCCP and other independent variables significantly affected the color characteristics ($P < 0.05$). Proteins, such as gelatin, present in the environment are among the factors affecting anthocyanin stability (Manzoor et al., 2021; Prajapati & Jadeja, 2022). Furthermore, anthocyanins are sensitive to sugar degradation products, and their degradation may occur during storage due to the reducing properties of saccharides in the composition (Hubbermann, 2024). This, in turn, impacts the color properties, stability and changes in the final product. Storage periods that may cause increases in pH, as well as environmental and compositional conditions, should be considered for the stability of anthocyanins (Bause et al., 2024). Moreover, positive and high correlations were observed between a* and hue angle, TPC and AAC, while negative correlations of other colour parameters were another remarkable finding (Table 2). A recent study by Wang and Hartel (2022) found that gelatine-based candy samples exhibited decreasing L* values and increasing a* and b* values after heat treatment. However, the study revealed that the influence of gelatine alone was minimal in the presence of BCCP, with significant interactions observed with coloring agents. The primary mechanisms leading to color alterations in sugar-containing gelatine gels are likely Maillard reactions and protein oxidations (Gunes et al., 2022). Sucrose inversion under the influence of shear forces and environmental factors such as temperature and pH may contribute to Maillard reactions by causing an increase in reducing sugar content. Furthermore, higher stirring speeds can increase the rate of protein oxidation reactions due to increased shear forces (Dalabasmaz et al., 2024). In addition to these, the interactions between sucrose and coloring agents should also be considered, according to the results of this study.

3.4. Antioxidant activity capacity and total phenolic content

Black carrot is a rich source of natural antioxidants. The variation in the antioxidant capacity levels may be influenced by several factors such as cultivar, growth conditions, developmental stage and the initial level compounds present (Özen et al., 2011). The relationship between polyphenols and AAC is a well-established and has been extensively studied. However, there is limited research on the interaction of coloring agents with other components in matrices, such as gummy candy, and their effects on total phenolic content (TPC) and AAC. In this study, TPC values for gummy candy samples ranged from 6.87 to 44.3 mg GAE/kg, while inhibition values for AAC were 0.00%–13.4% (Table 1). Significant linear models were identified for the effects of the independent

variables on TPC and AAC of the samples with R^2 values of 0.9397 and 0.9203, respectively. Although sugar and gelatine solution had negligible correlations (Supplementary File 1), the correlation coefficients for the BCCP were 0.969 and 0.959 for TPC and AAC, respectively (Table 2). As a result, it was determined that using BCCP increased the phenolic content of gummy candies, independent of the other components, thereby conferring to the AAC of these products. A study by Farhan et al. (2024) reported a significant improvement in the DPPH antioxidant activities of beetroot powder-added hard candies, increasing from 11.40 to 28.50 %. Similarly, a study reported by Moghaddas Kia et al. (2020), showed that the addition of 0.1–0.3% beet extract to gummy candies significantly ($p < 0.05$) improved DPPH activities from 32% to 48%, respectively.

3.5. Accelerated shelf life

In this study, the results of the changes in the colour and texture properties of the samples under accelerated shelf life conditions are presented in Table 4. In gummy candies, factors such as texture, water activity, moisture content, and color stability throughout the shelf life are of great importance. Monitoring these changes is critical in reformulation and enrichment studies. According to do Nascimento et al. (2023), significant increases in a* and b* values were observed during the storage period, while L* values remained relatively unchanged. The Maillard reactions were identified as one of the primary reasons for these changes.

The ΔE* values vary between 1.04 and 7.09 (Table 4). However, it is noteworthy that nearly 50% of the samples have ΔE* values of 3.0 and below. This is important because a ΔE* value above 3.0 indicates a visible colour change (Periche et al., 2015). Additionally, a recent study emphasized that the color stability of gummy candies containing encapsulated Lamduan anthocyanins (1.00–3.00 g/100 g) varied depending on storage temperature. At relatively high storage temperature (35 °C), increases in L* and b* values and decreases in a* values were observed. Therefore, using different anthocyanin sources and pre-processing effects, such as encapsulation materials and conditions, can lead to varying color stability behaviors in gummy samples.

A significant model for the effects of independent variables on texture change and ΔE* value could not be determined (Supplementary File 4). Additionally, moderate to strong interactions between the hardness variance ratio and ΔE* with other dependent and independent variables could not be identified (Table 2).

3.6. Optimization validation

In our study, optimization for gummy confectionery samples prepared with coloring agent was based on (i) texture profile analysis (maximum hardness and springiness), (ii) ΔE* value determined from accelerated shelf-life studies (minimum), and (iii) hardness change rate determined from accelerated shelf-life studies (minimum). Considering these responses, in samples prepared with BCCP, the optimum composition was determined to be 32.03 g/100g for sucrose, 21.0 g/100 g for gelatine solution, and 0.2743 g/100 g for BCCP concentration. The springiness and hardness values of the optimized gummy samples were predicted as 0.66 mm and 21.77 N values, respectively. The hardness and color parameters variation during the accelerated shelf life conditions were predicted as 3.87 and 33.66%. These values were validated experimentally, and the experimental results at the optimum point are given in Table 5. All the results are in the 95% confidential intervals (CI) level, confirming the model's validity and closeness between predicted and experimental results. FTIR and sensory analysis were conducted under optimized conditions, and the results were compared with the control gummy samples (without BCCP).

The determination of an optimum BCCP concentration lower than the commonly used ratio of 0.30 g/100 g in industrial applications (Hubbermann, 2024) is a noteworthy finding. Moreover, these results are significant as they reveal the interactions between major gummy components and hydrocolloids influencing the product stability. Identifying the mechanisms of these interaction(s) through further studies could provide substantial insights into confectionery technology. In these studies, the effects of BCCP on the structure formed by gelatin and its influence on binding sites can be particularly considered. Another key finding is that high concentrations of BCCP are not required to achieve color stability.

3.7. FTIR spectrum

The major components of the gummy candies are water, sugar, glucose syrup and gelatin. The peak at 3283.34 cm^{-1} corresponds to the stretching vibrations of hydroxyl groups of phenolic and water (Roudbari et al., 2024). This peak intensity increases with the inclusion of BCEP in the gummy formulation. The peak at 2929 cm^{-1} is attributed to the stretching vibrations of C–H bonds in carboxylic acids and NH_4 + bonds in free amino acids. This peak becomes more obvious in the optimized gummy samples (Fig. 2). Gelatin, key ingredient in gummy candies shows a prominent band related to gelatin (Amide I) in the spectral range of 1700–1600 cm−1 (Cebi et al., 2016). The intensity of the Amide I (1645 cm^{-1}) peak increased in the optimized gummy

Table 4
Color differences and texture properties variance ratios of samples under accelerated shelf-life conditions.

Sample	Hardness[a] (%)	Resilience[a] (%)	Cohesiveness[a] (%)	Springiness[a] (%)	Gumminess[a] (%)	Chewiness[a] (%)	$\Delta E_{a,b}$
1	13.5 ± 0.96^{ef}	15.2 ± 1.09^{c}	0.62 ± 0.03^{bc}	−28.0 ± 2.01^{g}	14.2 ± 0.06^{ef}	−17.6 ± 0.67^{f}	4.54 ± 0.98^{c}
2	36.8 ± 2.25^{c}	5.01 ± 0.66^{d}	2.58 ± 0.11^{ab}	12.2 ± 0.17^{e}	40.3 ± 2.09^{bc}	59.6 ± 2.67^{d}	6.34 ± 0.45^{a}
3	46.6 ± 2.45^{b}	−5.33 ± 0.45^{g}	0.72 ± 0.05^{bc}	47.4 ± 2.89^{b}	47.7 ± 3.08^{b}	117.5 ± 5.98^{a}	2.70 ± 0.19^{e}
4	36.5 ± 3.14^{c}	12.3 ± 1.03^{cd}	3.76 ± 0.08^{a}	29.6 ± 1.76^{d}	41.5 ± 1.56^{bc}	84.7 ± 3.98^{b}	5.63 ± 1.15^{b}
5	44.4 ± 4.01^{b}	3.86 ± 0.04^{de}	1.35 ± 0.05^{b}	19.0 ± 1.01^{de}	46.3 ± 3.09^{b}	73.8 ± 4.77^{c}	3.96 ± 0.46^{d}
6	57.0 ± 1.24^{a}	−2.04 ± 0.11^{f}	−1.02 ± 0.04^{d}	9.85 ± 0.76^{f}	55.2 ± 4.00^{a}	70.7 ± 1.98^{c}	2.69 ± 0.17^{e}
7	42.7 ± 0.98^{b}	1.02 ± 0.09^{e}	−3.22 ± 0.03	14.6 ± 0.99^{e}	48.9 ± 3.09^{b}	71.4 ± 4.25^{c}	3.64 ± 0.09^{d}
8	36.4 ± 2.44^{c}	−0.58 ± 0.05^{e}	1.40 ± 0.06^{b}	−39.8 ± 2.09^{i}	38.3 ± 2.09^{c}	−18.0 ± 1.07^{f}	3.96 ± 0.05^{d}
9	16.7 ± 0.77^{e}	3.28 ± 0.45^{de}	0.52 ± 0.02^{bc}	9.67 ± 0.09^{f}	17.3 ± 1.07^{e}	28.7 ± 2.11^{e}	2.72 ± 0.09^{e}
10	35.3 ± 1.45^{c}	7.47 ± 1.04^{d}	0.19 ± 0.02^{bc}	−33.6 ± 2.11^{h}	35.7 ± 2.11^{cd}	−10.7 ± 0.79^{f}	2.93 ± 0.03^{e}
11	33.0 ± 1.78^{c}	5.41 ± 0.09^{d}	0.47 ± 0.06^{bc}	17.1 ± 1.98^{de}	33.6 ± 1.76^{d}	56.4 ± 2.22^{d}	5.49 ± 0.91^{b}
12	34.5 ± 1.96^{c}	7.71 ± 0.32^{d}	−1.09 ± 0.03^{d}	28.4 ± 2.01^{d}	32.6 ± 1.09^{d}	70.0 ± 2.04^{c}	6.50 ± 0.07^{a}
13	28.7 ± 2.11^{d}	15.5 ± 0.98^{c}	3.12 ± 0.21^{a}	35.5 ± 3.01^{c}	32.7 ± 2.05^{d}	79.5 ± 2.98^{bc}	2.10 ± 0.19^{ef}
14	43.5 ± 4.21^{b}	12.1 ± 1.11^{cd}	−0.04 ± 0.02^{c}	−40.6 ± 0.98^{i}	43.4 ± 3.11^{b}	−94.0 ± 2.11^{h}	1.93 ± 0.05^{f}
15	19.4 ± 1.09^{de}	19.1 ± 2.01^{b}	−0.93 ± 0.02^{c}	43.1 ± 3.21^{b}	18.3 ± 0.96^{e}	−96.2 ± 3.99^{h}	2.98 ± 0.04^{de}
16	7.01 ± 0.33^{f}	28.6 ± 2.02^{a}	2.57 ± 0.12^{ab}	57.7 ± 2.09^{a}	9.84 ± 0.67^{f}	−84.6 ± 4.16^{g}	3.71 ± 0.12^{d}

[a] According to differences between Day 0 and Day 63 under 25 °C and 70% relative humidity conditions. Mean ± standard deviation. The same superscript lowercase letters in each column indicate no significant differences ($P < 0.05$).

Table 5
Optimization of process conditions and validation.

Factor A	Factor B	Factor C	Response1	Response 2	Response 3	Response 4
Sucrose (g/100 g)	Gelatin Solution (g/100 g)	BCCP (g/100 g)	Springiness (mm)	Hardness (N)	ΔE[a] value	Hardness Variation (%)
32.03	21	0.2743	0.66	21.77	3.87	33.6551
Experimental Results						
	95%CI low for mean		Observed		95%CI high for mean	
Springiness (%)	0.37		0.61		0.95	
Hardness (g)	18.73		19.26		24.81	
ΔE value	3.09		3.68		4.64	
Hardness Variation (%)	12.11		22.35		55.20	

[a] CI: Confidential Intervals; BCCP; Black Carrot Concentrate Powder.

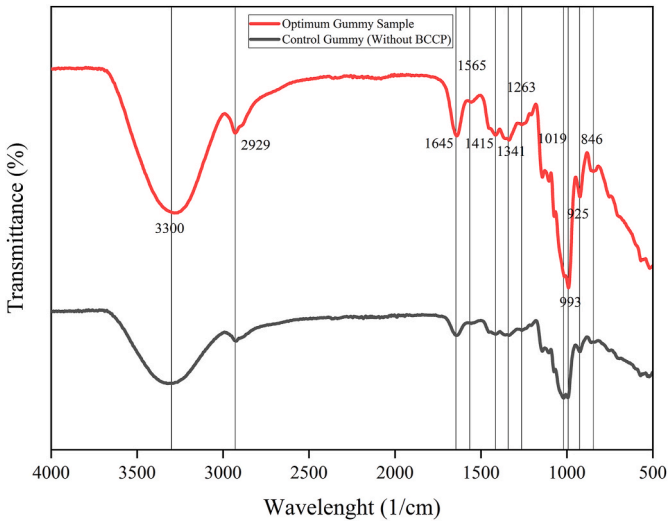

Fig. 2. FTIR spectra of BCCP-added and not-added gummies at the optimum point.

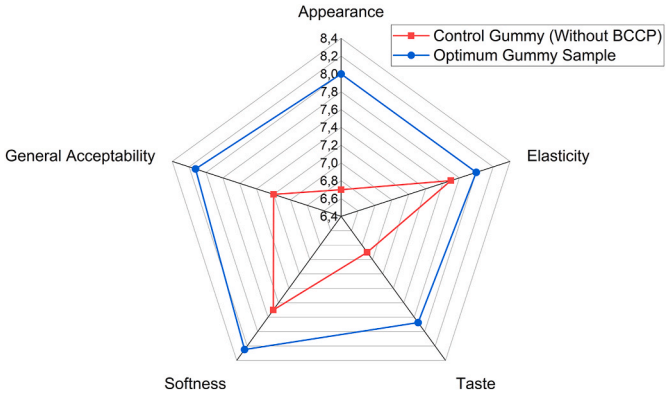

Fig. 3. Sensorial evaluation of BCCP-added and not-added gummies at the optimum point indicates insignificant differences ($P > 0.05$) according to the independent *t*-test.

samples. The spectral range between 1500 and 1200 cm^{-1} is a mixed region affected by the bending of -CH_2 and -CH_3 groups in proteins and C-H bending vibrations of carbohydrates. 1415 cm^{-1} displays carbohydrates' O-H stretching/bending vibrations (Tewari & Irudayaraj, 2004). This peak seems similar to the control gummy sample. The relatively strong absorption peaks at around 1019 cm^{-1} of the samples reflect the absorption of the pyran ring, and this peak weakens in the optimized sample. The band observed around 993 cm^{-1} is the characteristic vibrational band of the glycosidic bond of sucrose. All gummy candies were prepared, including sucrose in their compositions. The peaks observed around 925 cm^{-1} arise from the C-H bending, and this peak's intensity increases in the optimized sample. In the literature, the bands obtained with BCP extract were found as 3300 cm^{-1} (OH symmetric stretching vibration), 1637 cm^{-1} (C=C shear on the phenolic group), 1590 cm^{-1} (C=N vibration), 1449 cm^{-1} (asymmetric ring vibration on plane), 1378 cm^{-1} (CH deformation) and 1073 cm^{-1} (phenolic ring C-H asymmetric stretching) (Kaur et al., 2023). Especially increases in OH symmetric stretching vibration, C=C shear on the phenolic group, and CH deformation bands confirmed the presence of anthocyanins in the optimized gummy samples.

3.8. Sensory analysis

Gummy samples were prepared using a composition determined from the results of the characterization and accelerated shelf-life studies. The sensory scores for the control (without BCCP) and optimum gummy samples are shown in Fig. 3. The addition of BCCP into the gummy formulation improved the appearance, structure, and taste parameters compared to the control samples, however differences were not statistically significant ($p > 0.05$). The elasticity was found to be similar to the control sample. The general acceptability score of BCCP-added samples was higher by 1 point than that of the control sample; however, this effect was also not statistically significant ($p > 0.05$). In the literature, beetroot powder-supplemented hard candies improved the color profile due to the presence of coloring pigments such as betaxanthin, betacyanin, and betalain. However, the sensory scores for taste decreased due to the astringent compounds in beetroot, such as tannins, geosmin, and isothiocyanates (Farhan et al., 2024). The sensory evaluations in this study showed that the use of BCCP in gummy formulations resulted in good acceptance of the gummy confectionery samples.

4. Conclusion

This study investigated the effects of varying gelatin and sucrose ratios on product properties through the use of different concentrations of BCCP in gummy formulations. Significant linear, quadratic, and cubic models were identified for the effects of independent variables on dependent variables, such as hardness, resilience, chewiness, cohesiveness, total phenolic content, antioxidant activity, color parameters L*, a*, b*, chroma, hue angle, and pH ($P < 0.05$). The R^2 values of these models were between 0.4213 and 0.9999. Notably, significant interactions were observed between colorant x gelatine and colorant x sucrose and were significant for texture parameters such as hardness, chewiness, cohesiveness, and for L*, a*, b*, and chroma values ($P < 0.05$). For optimization of gummy confectionery production, texture profile analysis (maximum hardness and springiness), ΔE* value determined from accelerated shelf-life studies (minimum), and hardness variance ratio, determined from accelerated shelf-life studies (minimum), were considered. Based on these responses, the optimal composition for samples prepared with BCCP was determined to be 32.03 g/100g for sucrose, 21.0 g/100g for gelatin solution, and 0.2743 g/100g

for BCCP. The optimized gummy samples produced at these conditions, and the results were compared to predicted values. All the results are in the 95% confidential intervals (CI) level, confirming the model's validity and closeness between predicted and experimental results. The FTIR and sensory analysis were carried out at the optimum points. Peaks related to stretching vibrations of hydroxyl groups of phenolic and water, stretching vibrations of C–H bonds in carboxylic acids, and NH_4 + bonds in free amino acids, Amide I and C-H bending peaks were intensified with the addition of BCCP into the formulation. Adding BCCP into the gummy formulation improved the appearance, structure, and taste parameters compared to the control samples, but the differences were insignificant ($p > 0.05$). This study suggests that the selection of colorants should take into account the properties of the food materials and the interactions between product components and colorants. Interactions between product components and colorants should also be considered. In further studies, it is recommended to (i) determine the effects of different natural colorants on quality properties other than color and product stability in gummy and other confectionery products, (ii) investigate the interactions between sugar profiles and colorants, (iii) investigate the interactions between gelatin bloom degree and the amount of colorant used. Additionally, understanding the impact of environmental conditions in different consumption regions (e.g., relative humidity, temperature) on final product quality and colorant stability is crucial. Furthermore, determining and modeling interactions among components in the context of climate change scenarios could contribute to producers' adaptation to these changes. The data obtained from this study could be valuable for addressing these issues and providing insights for producers in enhancing product quality.

CRediT authorship contribution statement

Ilyas Atalar: Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Betul Ozen:** Formal analysis. **Derya Genc Polat:** Formal analysis. **Emine Han:** Formal analysis. **Omer Said Toker:** Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Ibrahim Palabiyik:** Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Tahra ElObeid:** Writing – review & editing, Validation, Software, Methodology, Data curation, Conceptualization. **Nevzat Konar:** Writing – review & editing, Validation, Software, Project administration, Methodology, Investigation, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2025.117443.

Data availability

Data will be made available on request.

References

Aidat, O., Belkacemi, L., Belalia, M., Zainol, M., & Barhoum, H. S. (2023). Physicochemical, rheological, and textural properties of gelatin extracted from chicken by-products (feet-heads) blend and application. *International Journal of Gastronomy and Food Science, 32*(January), Article 100708. https://doi.org/10.1016/j.ijgfs.2023.100708

Amjadi, S., Ghorbani, M., Hamishehkar, H., & Roufegarinejad, L. (2018). Improvement in the stability of betanin by liposomal nanocarriers: Its application in gummy candy as a food model. *Food Chemistry, 256*, 156–162. https://doi.org/10.1016/j.foodchem.2018.02.114

Bause, K., Bußler, S., de Munnik, M., Reineke, K., van den Berg-Stolp, F., Zanders, F., & Zillekens, A. (2024). Chapter 24 - challenges and opportunities in the use of natural colors in foods and beverages: An industrial perspective. In R. Schweiggert (Ed.), *Handbook on natural pigments in food and beverages* (2nd ed., pp. 577–604). Woodhead Publishing. https://doi.org/10.1016/B978-0-323-99608-2.00013-6. Second Edi.

Brand-Williams, W., Cuvelier, M. E., & Berset, C. (1995). Use of a free radical method to evaluate antioxidant activity. *LWT - Food Science and Technology, 28*(1), 25–30. https://doi.org/10.1016/S0023-6438(95)80008-5

Burey, P., Bhandari, B. R., Rutgers, R. P. G., Halley, P. J., & Torley, P. J. (2009). Confectionery gels: A review on formulation, rheological and structural aspects. *International Journal of Food Properties, 12*(1), 176–210. https://doi.org/10.1080/10942910802223404

Cao, X., Zhang, Y., Zhang, F., Wang, Y., Yi, J., & Liao, X. (2011). Effects of high hydrostatic pressure on enzymes, phenolic compounds, anthocyanins, polymeric color and color of strawberry pulps. *Journal of the Science of Food and Agriculture, 91*(5), 877–885. https://doi.org/10.1002/jsfa.4260

Casas-Forero, N., Moreno-Osorio, L., Orellana-Palma, P., & Petzold, G. (2021). Effects of cryoconcentrate blueberry juice incorporation on gelatin gel: a rheological, textural and bioactive properties study. *Lwt, 138*(November 2020), 110674. https://doi.org/10.1016/j.lwt.2020.110674.

Casas-Forero, N., Trujillo-Mayol, I., Zúñiga, R. N., Petzold, G., & Orellana-Palma, P. (2022). Effects of cryoconcentrated blueberry juice as functional ingredient for preparation of commercial confectionary hydrogels. *Gels, 8*(4), 217. https://doi.org/10.3390/gels8040217

Cavalcanti, R. N., Santos, D. T., & Meireles, M. A. A. (2011). Non-thermal stabilization mechanisms of anthocyanins in model and food systems - an overview. *Food Research International, 44*(2), 499–509. https://doi.org/10.1016/j.foodres.2010.12.007.

Cebi, N., Dogan, C. E., Mese, A. E., Ozdemir, D., Arıcı, M., & Sagdic, O. (2019). A rapid ATR-FTIR spectroscopic method for classification of gelatin gummy candies in relation to the gelatin source. *Food Chemistry, 277*, 373–381. https://doi.org/10.1016/j.foodchem.2018.10.125

Cebi, N., Durak, M. Z., Toker, O. S., Sagdic, O., & Arici, M. (2016). An evaluation of Fourier transforms infrared spectroscopy method for the classification and discrimination of bovine, porcine and fish gelatins. *Food Chemistry, 190*, 1109–1115. https://doi.org/10.1016/j.foodchem.2015.06.065

Dalabasmaz, S., Melayim, M. E., & Konar, N. (2024). Effects of gelatin concentration, adding temperature and mixing rate on texture and quality characteristics of model gels. *Journal of Texture Studies, 55*(1), Article e12800. https://doi.org/10.1111/jtxs.12800

do Nascimento, R. R., Pimentel, T. C., Garcia, S., & Prudencio, S. H. (2023). Acacia gum candy with Limosilactobacillus reuteri and lemongrass essential oil: Effect of storage time on physicochemical characteristics and probiotic survival. *Food Bioscience, 56*, Article 103128. https://doi.org/10.1016/j.fbio.2023.103128

Dufour, C., & Sauvaitre, I. (2000). Interactions between anthocyanins and aroma substances in a model system. Effect on the flavor of grape-derived beverages. *Journal of Agricultural and Food Chemistry, 48*(5), 1784–1788. https://doi.org/10.1021/jf990877l.

Ergun, R., Lietha, R., & Hartel, R. W. (2010). Moisture and shelf life in sugar confections. *Critical Reviews in Food Science and Nutrition, 50*(2), 162–192. https://doi.org/10.1080/10408390802248833

Fan, K., Zhang, M., & Mujumdar, A. S. (2017). Application of airborne ultrasound in the convective drying of fruits and vegetables: A review. *Ultrasonics Sonochemistry, 39*, 47–57.

Farhan, M., Ahmad, Z., Waseem, M., Mehmood, T., Javed, M. R., Ali, M., Manzoor, M. F., & Goksen, G. (2024). Assessment of Beetroot powder as nutritional, antioxidant, and sensory evaluation in candies. *Journal of Agriculture and Food Research, 15*, Article 101023. https://doi.org/10.1016/j.jafr.2024.101023

Ge, H., Wu, Y., Woshnak, L. L., & Mitmesser, S. H. (2021). Effects of hydrocolloids, acids and nutrients on gelatin network in gummies. *Food Hydrocolloids, 113*, Article 106549. https://doi.org/10.1016/j.foodhyd.2020.106549

Gérard, V., Ay, E., Morlet-Savary, F., Graff, B., Galopin, C., Ogren, T., … Lalevée, J. (2019). Thermal and photochemical stability of anthocyanins from black carrot, grape juice, and purple sweet potato in model beverages in the presence of ascorbic acid. *Journal of Agricultural and Food Chemistry, 67*(19), 5647–5660. https://doi.org/10.1021/acs.jafc.9b01672.

Gok, S., Toker, O. S., Palabiyik, I., & Konar, N. (2020). Usage possibility of mannitol and soluble wheat fiber in low calorie gummy candies. *LWT–Food Science and Technology, 128*, Article 109531. https://doi.org/10.1016/j.lwt.2020.109531

Göztok, S. P., Palabiyik, I., Bölük, E., Gunes, R., Toker, O. S., & Konar, N. (2023). Determination and numerical modeling of sugar release from model food gels. *Journal of Food Engineering, 338*, Article 111262. https://doi.org/10.1016/j.jfoodeng.2022.111262

Gunes, R., Palabiyik, I., Konar, N., & Said Toker, O. (2022a). Soft confectionery products: Quality parameters, interactions with processing and ingredients. *Food Chemistry, 385*, Article 132735. https://doi.org/10.1016/j.foodchem.2022.132735

Gunes, R., Palabiyik, I., Konar, N., & Said Toker, O. (2022b). Soft confectionery products: Quality parameters, interactions with processing and ingredients. *Food Chemistry, 385*, Article 132735. https://doi.org/10.1016/j.foodchem.2022.132735

Hartel, R. W., von Elbe, J. H., & Hofberger, R. (2018). Confectionery science and technology. In *Confectionery science and technology* (Vol. 536). Springer. https://doi.org/10.1007/978-3-319-61742-8

Herbach, K. M., Stintzing, F. C., & Carle, R. (2006). Betalain stability and degradation—structural and chromatic aspects. *Journal of Food Science, 71*(4), R41–R50.

Hu, F., Song, Y. Z., Li, J. Y., Thakur, K., Zhang, J. G., & Wei, Z. J. (2024). Lycium barbarum pulp addition improves the dough properties and gluten protein structure. *Food Chemistry X, 23*, Article 101773. https://doi.org/10.1016/j.fochx.2024.101773

Hubbermann, E. M. (2016). Coloring of low-moisture and gelatinized food products. In R. Carle, R. M. B, T.-H. on, N. P. in F, & B. Schweiggert (Eds.), *Handbook on natural pigments in food and beverages: Industrial applications for improving food color* (pp. 179–196). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100371-8.00008-7.

Hubbermann, E. M. (2024). Chapter 11 - coloring of low-moisture and gelatinized food products. In R. Schweiggert (Ed.), *Handbook on natural pigments in food and beverages* (2nd ed., pp. 265–281). Woodhead Publishing. https://doi.org/10.1016/B978-0-323-99608-2.00005-7. Second Edi.

Ingemann Berentzen, E., Hauer Møller, A., Danielsen, M., Jensen, M., Joernsgaard, B., & Kastrup Dalsgaard, T. (2024). Stability of individual anthocyanins from black carrots stored in light and darkness – impact of acylation. *Food Research International, 186*. https://doi.org/10.1016/j.foodres.2024.114382.

Kaderides, K., Solomakou, N., Mourtzinos, I., & Goula, A. M. (2024). Chapter 11 - spray drying encapsulation of natural food colorants. In S. M. Jafari, & K. Samborska (Eds.), *Spray drying for the food industry* (pp. 303–337). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-819799-8.00016-8.

Kaur, G., Sharma, N., Singh, A., Kapoor, S., & Khatkar, S. K. (2023). Ultrasound-assisted microemulsions of anthocyanins extracted from black carrot pomace and its utilisation as functional component in kulfi: Implication on in vitro release, bio-functional components and rheological characteristics. *International Journal of Food Science and Technology, 58*(5), 2744–2753. https://doi.org/10.1111/ijfs.16102

Konar, N., Gunes, R., Palabiyik, I., & Toker, O. S. (2022). Health conscious consumers and sugar confectionery: Present aspects and projections. *Trends in Food Science and Technology, 123*, 57–68. https://doi.org/10.1016/j.tifs.2022.02.001

Kowalski, S. J., Mierzwa, D., & Stasiak, M. (2017). Ultrasound-assisted convective drying of apples at different process conditions. *Drying Technology, 35*(8), 939–947.

Lan, T., Qian, S., Song, T., Zhang, H., & Liu, J. (2023). The chromogenic mechanism of natural pigments and the methods and techniques to improve their stability: a systematic review. Food Chemistry, 407(November 2022), 134875. https://doi.org/10.1016/j.foodchem.2022.134875.

Li, C., Zheng, Y., Xiong, X., & Xue, F. (2025). Production of protein-epigallocatechin gallate conjugates using free radicals induced by ultrasound and their gelation behavior. *Food Chemistry, 463*(P3), Article 141300. https://doi.org/10.1016/j.foodchem.2024.141300

Lin, D., Xiao, L., Wen, Y., Qin, W., Wu, D., Chen, H., … Zhang, Q.. Comparison of apple polyphenol-gelatin binary complex and apple polyphenol-gelatin-pectin ternary complex: Antioxidant and structural characterization. Lwt, 148(October 2020). https://doi.org/10.1016/j.lwt.2021.111740.

Manzoor, M., Singh, J., Gani, A., & Noor, N. (2021). Valorization of natural colors as health-promoting bioactive compounds: Phytochemical profile, extraction techniques, and pharmacological perspectives. *Food Chemistry, 362*, Article 130141. https://doi.org/10.1016/j.foodchem.2021.130141

Moghaddas Kia, E., Ghaderzadeh, S., Mojaddar Langroodi, A., Ghasempour, Z., & Ehsani, A. (2020). Red beet extract usage in gelatin/gellan based gummy candy formulation introducing Salix aegyptiaca distillate as a flavouring agent. *Journal of Food Science and Technology, 57*(9), 3355–3362. https://doi.org/10.1007/s13197-020-04368-8

Montilla, E. C., Arzaba, M. R., Hillebrand, S., & Winterhalter, P. (2011). Anthocyanin composition of black carrot (Daucus carota ssp. sativus var. atrorubens Alef.) Cultivars antonina, beta sweet, deep purple, and purple haze. *Journal of Agricultural and Food Chemistry, 59*(7), 3385–3390. https://doi.org/10.1021/jf104724k.

Özen, G., Akbulut, M., & Artik, N. (2011). Stability of black carrot anthocyanins in the Turkish delight (LOKUM) during storage. *Journal of Food Process Engineering, 34*(4), 1282–1297. https://doi.org/10.1111/j.1745-4530.2009.00412.x

Pekdogan Goztok, S., Gunes, R., Toker, O. S., Palabiyik, I., & Konar, N. (2022). Investigation of the use of various fruit juice concentrates instead of corn syrup in marshmallow type products: a preliminary study. *International Journal of Gastronomy and Food Science, 30*, 100616. https://doi.org/10.1016/j.ijgfs.2022.100616.

Periche, A., Heredia, A., Escriche, I., Andrés, A., & Castelló, M. L. (2015). Potential use of isomaltulose to produce healthier marshmallows. *LWT–Food Science and Technology, 62*(1), 605–612. https://doi.org/10.1016/j.lwt.2014.12.024

Pizzoni, D., Compagnone, D., Di Natale, C., D'Alessandro, N., & Pittia, P. (2015). Evaluation of aroma release of gummy candies added with strawberry flavours by gas-chromatography/mass-spectrometry and gas sensors arrays. *Journal of Food Engineering, 167*, 77–86. https://doi.org/10.1016/j.jfoodeng.2015.03.003

Pour Hosseini, S. R., Tavakoli, O., & Sarrafzadeh, M. H. (2017). Experimental optimization of SC-CO2 extraction of carotenoids from Dunaliella salina. *The Journal of Supercritical Fluids, 121*, 89–95. https://doi.org/10.1016/j.supflu.2016.11.006

Prajapati, R. A., & Jadeja, G. C. (2022). Natural food colorants: Extraction and stability study. *Materials Today: Proceedings, 57*, 2381–2395. https://doi.org/10.1016/j.matpr.2021.12.151

Raj, R., Sheikh, S. A., Singh, S. A., & Shetty, N. P. (2024). Improvement of storage stability and bioaccessibility of microencapsulated black carrot (Daucus Carota ssp. sativus) anthocyanins using maltodextrin and sericin protein combinations as wall material. *Food Bioscience, 61*, Article 104666. https://doi.org/10.1016/j.fbio.2024.104666

Roudbari, M., Barzegar, M., Sahari, M. A., & Gavlighi, H. A. (2024). Formulation of functional gummy candies containing natural antioxidants and stevia. *Heliyon, 10*(11), Article e31581. https://doi.org/10.1016/j.heliyon.2024.e31581

Sadilova, E., Stintzing, F. C., Kammerer, D. R., & Carle, R. (2009). Matrix dependent impact of sugar and ascorbic acid addition on color and anthocyanin stability of black carrot, elderberry and strawberry single strength and from concentrate juices upon thermal treatment. *Food Research International, 42*(8), 1023–1033. https://doi.org/10.1016/j.foodres.2009.04.008.

Saint-Eve, A., Déléris, I., Panouillé, M., Dakowski, F., Cordelle, S., Schlich, P., & Souchon, I. (2011). How texture influences aroma and taste perception over time in candies. *Chemosensory Perception, 4*(1–2), 32–41. https://doi.org/10.1007/s12078-011-9086-4.

Sakulnarmrat, K., & Konczak, I. (2022). Encapsulation of Melodorum fruticosum Lour. anthocyanin-rich extract and its incorporation into model food. *LWT–Food Science and Technology, 153*, Article 112546. https://doi.org/10.1016/j.lwt.2021.112546

Statista. (2024). Available at: https://www.statista.com/outlook/cmo/food/confectionery-snacks/confectionery/worldwide (Accessed 3 October 2024).

Su, K., Brunet, M., Festring, D., Ayed, C., Foster, T., & Fisk, I. (2021). Flavour distribution and release from gelatine-starch matrices. *Food Hydrocolloids, 112*, Article 106273. https://doi.org/10.1016/j.foodhyd.2020.106273

Subramaniam, P. (2016). The stability and shelf life of food. In *The stability and shelf life of food*. Elsevier Science. https://doi.org/10.1016/C2015-0-06842-3.

Tewari, J., & Irudayaraj, J. (2004). Quantification of saccharides in multiple floral honeys using fourier transform infrared microattenuated total reflectance spectroscopy. *Journal of Agricultural and Food Chemistry, 52*(11), 3237–3243. https://doi.org/10.1021/jf035176+

Thakur, M., & Modi, V. K. (2024). Biocolorants in food: sources, extraction, applications and future prospects. *Critical Reviews in Food Science and Nutrition, 64*(14), 4674–4713. https://doi.org/10.1080/10408398.2022.2144997.

Wang, R., & Hartel, R. W. (2022). Citric acid and heating on gelatin hydrolysis and gelation in confectionery gels. *Food Hydrocolloids, 129*, Article 107642. https://doi.org/10.1016/j.foodhyd.2022.107642

Wang, R., Hartel, R.W., Zhai, X., Fu, W., Sun, Y., & Wang, S. (2024). Phase separation and gelation of gelatin-glucose syrup mixtures and gummy confections: effects of moisture content, sugars, citric acid, and citrates. Food Hydrocolloids, 153(March), 110006. https://doi.org/10.1016/j.foodhyd.2024.110006.

Wang, R., Zhai, X., Hartel, R. W., Chang, Y., Pang, W., Han, W., Lv, H., & Wang, S. (2024). Effects of saccharide type and extended heating on the Maillard reaction and physicochemical properties of high-solid gelatin gels. *Food Chemistry, 459*, Article 140249. https://doi.org/10.1016/j.foodchem.2024.140249

Xie, D., Hu, H., Huang, Q., & Lu, X. (2023). Development and characterization of food-grade bigel system for 3D printing applications: Role of oleogel/hydrogel ratios and emulsifiers. *Food Hydrocolloids, 139*, Article 108565. https://doi.org/10.1016/j.foodhyd.2023.108565

Xiong, S., Melton, L. D., Easteal, A. J., & Siew, D. (2006). Stability and antioxidant activity of black currant anthocyanins in solution and encapsulated in glucan gel. *Journal of Agricultural and Food Chemistry, 54*(17), 6201–6208. https://doi.org/10.1021/jf060889o.

Zhao, H., Kang, X., Zhou, X., Tong, L., Yu, W., Zhang, J., Yang, W., Lou, Q., & Huang, T. (2021). Glycosylation fish gelatin with gum Arabic: Functional and structural properties. *LWT–Food Science and Technology, 139*, Article 110634. https://doi.org/10.1016/j.lwt.2020.110634