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ORIGINAL RESEARCH PAPER

ASSESSMENT OF ACRYLAMIDE AND 5 HYDROXYMETHYLFURFURAL LEVELS AND RELATED PARAMETERS IN MARKET PURCHASED TURKISH DESSERTS

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Abstract

This study investigated the physicochemical properties and Maillard reaction contaminants of traditional desserts (Şambali, Halka, and Lokma) marketed in Aydın province of Türkiye, and evaluated differences according to dessert type, supply source (patisserie vs. vendor), and district using chemometric approaches. Samples were classified based on product type, place of supply, and geographic location, and analyzed using correlation analysis, principal component analysis (PCA), cluster analysis, and heat maps.

Results showed that physical and chemical characteristics were not uniform across the supply chain, reflecting differences in formulation, shaping practices, and processing conditions.HMF and acrylamide levels varied according to both production practices and regional factors. Frying conditions and cereal matrix differences were identified as critical determinants of acrylamide formation. Desserts from patisseries generally exhibited higher acrylamide levels, whereas vendor products showed comparatively elevated HMF concentrations. A broad range of HMF (0.00–50.63 mg/kg) and AA (179.90-570.72 µg/kg) concentrations were detected, with the highest levels found in Halka desserts. Correlation analysis indicated that HMF was more closely associated with baking-related physical parameters, while acrylamide was linked to chemical matrix characteristics, particularly trace elements. Multivariate analyses (PCA and heat map clustering) consistently demonstrated that sample differentiation was driven by the combined effects of compositional and physical variables. These findings highlight the importance of standardized processing and mitigation strategies to reduce contaminant formation in traditional syrup-based desserts.

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Keywords: dessert, Maillard reaction, acrylamide, HMF, multivariate analyses

Introduction

Chemical contamination is defined as the presence of chemicals in places where they were not expected to be. It also refers to chemical quantities greater than a certain threshold value (Perveen, 2023). Various hazardous chemicals are produced during food processing operations (Onyeaka *et al.*, 2024; Pathak *et al.*, 2022). Although high-temperature cooking may improve the flavor, texture and overall quality, it also results in different hazardous compounds and chemicals (toxicants, carcinogens, mutagens). Such compounds and chemicals may pose serious consumer health risks. Maillard reaction is encountered at high temperatures. The reaction of amino acids with reducing sugars may result in various chemicals (Vignesh *et al.,* 2024). Acrylamide and HMF are predominantly formed in baked products through the Maillard reaction and are recognized as major heat-derived contaminants (Capuano and Fogliano 2011). In addition to the Maillard reaction, HMF can also be formed via caramelization of sugars. During caramelization, sugars undergo enolization and dehydration to form fructofuranosyl cations and leading to HMF formation (Şahiner *et al.*, 2025).

Acrylamide is a carcinogenic compound. It is usually formed through frying or baking starchy ingredients at high temperatures (Ehsanur Rahman *et al.,* 2023). Just because of health hazards, the United Nations Joint FAO/WHO Expert Committee on Food Additives and European Food Safety Authority has limited dietary exposure to acrylamide (Hu *et al.*, 2017). Although no national regulation exists in Türkiye, European Union (EU) regulation legal limit for acrylamide is less than 300 μg/kg for products like biscuits, wafers, crackers, crispbreads (EU, 2017/2158). Several studies have also reported that acrylamide exposure may cause various birth anomalies (Hogervorst *et al.*, 2022), neurotoxic effects on the peripheral, autonomic and central nervous systems (Lindeman *et al.*, 2021; Zhao *et al.*, 2022), and increase the risk of developing several types of cancer, including lung cancer, prostate cancer (Morales *et al.*, 2014), and breast cancer (Filippini, *et al.,* 2022). The 5- Acrylamide is primarily formed through the Maillard reaction between free asparagine and reducing sugars (such as glucose and fructose) at high temperatures (Muttucumaru *et al.* 2017). Reactive carbonyl compounds generated during sugar degradation and lipid oxidation may also contribute to its formation (Capuano, 2016).

The 5-Hydroxymethylfurfural (HMF), another Maillard reaction contaminant, is mainly formed through dehydration of hexose sugars under acidic and thermal conditions (Capuano and Fogliano, 2011; Choudhary *et al.*, 2020). HMF has been associated with DNA damage, mutations and several chronic diseases including diabetes and cardiovascular disorders (Kathuria *et al.,* 2023). Products rich in reducing sugars are therefore susceptible to HMF formation during thermal processing. Additionally, prolonged storage and high-temperature conditions may further increase HMF levels (Buvé *et al.,* 2021). Thus, processing conditions such as frying temperature and cooking time are critical factors affecting the formation of acrylamide and HMF in foods (Mousavi Khaneghah *et al.*, 2020).

Turkish cuisine is mostly composed of carbohydrates. Syrup-desserts also hold a significant place in Middle Eastern and Turkish cuisines (Yıldırım *et al.*, 2018). A face-to-face survey conducted with 166 participants revealed that 97.74% of them consumed syrup-based desserts. Additionally, 39.34% of consumers preferred to have desserts in the evening diet and 6.45% ate them daily, 13.71% consumed them 2-4 days a week, 18.55% once a week, 36.29% every two weeks and 25% once a month (Abdikoğlu *et al.*, 2018). A study conducted in Adana province within the scope of UNESCO's Creative Cities Network for Gastronomy mentioned that desserts like "Halka tatlı" "Burma tatlı", "Taş kadayıf", "Şam tatlısı" and "Tulumba tatlısı" were among the most consumed syrup-based traditional sweets (Şahin and Ünlüönen, 2021). It was also observed that visitors to Adana's international carnival had eaten or planned to eat desserts such as "Halka" (29%) and "Şambali" (10.4%) (Karaca *et al.*, 2017). "Halka tatlı" was also identified as one of the most consumed street desserts (Bektarım *et al.*, 2019).

Halka dessert is prepared by mixing wheat flour, water and yeast and allowing the dough to ferment for 30 min. Next, the dough is placed into frying oil at a temperature range of 230-250ºC for 2-4 min, resulting in a serrated, ring shape. The fried dough is then quickly immersed into syrup at room temperature (Özer *et al.*, 2012). Lokma dessert is produced by frying dough made with flour, yeast, water and salt, then immersing into the syrup (Yıldız, 2020). Lokma has a small, spherical shape in contrast to Halka (Özer *et al.*, 2012). Şambali is a syrup-based dessert made from semolina, sugar and milk and is decorated with peanuts on top before being baked (Yıldız, 2020). These desserts are exposed to intense thermal processing and contain high levels of carbohydrates, making them susceptible to Maillard reaction contaminant formation.

In Turkey, there have been limited studies on Maillard reaction contaminants encountered in traditional desserts. Turkish syrup desserts like Baklava, Halka, Tulumba and Lokma were reported to have acrylamide levels of between 25 - 132 µg/kg piece (Özer *et al.*, 2012). Glyoxal, a Maillard reaction product, levels of Baklava were reported as between 344 - 815 µg/100 g and methylglyoxal levels as between 19 - 358 µg/100 g piece (Uğur *et al.*, 2022). In another study, 311 traditional Turkish foods, especially desserts obtained from Turkish markets were analyzed for their acrylamide content. It was observed that syrup-soaked fried pastries made from unleavened dough lump had an acrylamide content of 193 µg/kg, Tulumba 241 µg/kg, Kadayıf ≤10 µg/kg, Kemalpasa dessert 512 µg/kg piece (Ölmez *et al.*, 2008). Recently, acrylamide and HMF levels of tray Kadayif dessert samples under different additives, additive levels and frying times were investigated by Seyyedcheraghi *et al.* (2023). In none of the above-mentioned studies, both acrylamide and HMF levels haven't been investigated in traditional Şambali, Halka and Lokma desserts despite high consumption levels in Türkiye as well as in the Middle East region. Additionally, information on the correlation of HMF and acrylamide with physicochemical properties was not provided.

Various studies have been conducted in several countries on the occurrence of Maillard reaction products in foods (Lipinski *et al.*, 2024; Arsisseto *et al.*, 2012; Hoxha *et al.*, 2019). However, there is no data on places of supply, provided locations and type of dessert to determine chemical contamination source of hazards. Therefore, objective of this study was set as to determine acrylamide and HMF levels in common Turkish desserts (Lokma, Halka, Şambali) and to provide a comprehensive database for the occurrence of these contaminants. Correlations of acrylamide and HMF with some quality traits were also investigated. Additionally, chemometric methods such as cluster analysis, heat maps and PCA were used to discriminate dessert samples in terms of HMF and acrylamide formation.

Materials and methods

Samples

A total of 78 traditional syrup dessert samples (26 Şambali, 26 Halka and 26 Lokma) were taken from randomly selected 13 patisserie and 13 street vendors in Efeler, Nazilli, Söke, Kuşadası and Didim districts of Aydın province, where most local and foreign tourists visit. Samples were obtained from the different and the most crowded districts of Aydın province (Efeler 29, Nazilli 16, Söke 12, Kuşadası 12, Didim 9) (Figure 1). Selected desserts are highly consumed and expected to contain acrylamide and HMF, since they were produced by heat treatment. Samples were divided into sub-groups based on types, place of supply and locations where desserts were purchased, so as to allow the comparison between different desserts on the basis of source of food safety hazard. All the samples were homogenized and stored at +4 °C in polyethylene bags until analysis.

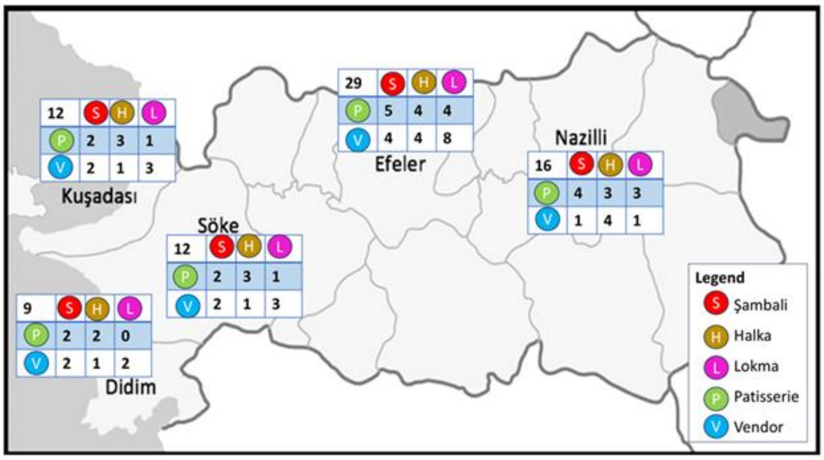

Figure 1. Sampling location.

Chemicals and reagents

The experiments exclusively used solvents and chemicals of analytical grade, all readily available for commercial purchase. Petrolium ether for chemical analyses was obtained from Isolab B.V. Nitric acid (65%) and hydrogen peroxide solution (30%) were used for mineral analyses and supplied from Sigma-Aldrich (Taufkirchen, Germany). The analytical grade reagents were obtained for HMF and acrylamide experiments, including acrylamide (analytical standard, ≥ 99.0%), Carrez I and Carrez II solutions, HMF (analytical standard, ≥ 98.0%), sodium thiosulfate, n-hexane, potassium bromide, hydrobromic acid, triethylamine were sourced from Sigma-Aldrich. Methanol, ethyl acetate and ultrapure water were provided by Merck (Darmstadt, Germany).

Physical properties and color analysis

Width, length and diameter (height) of dessert samples were measured with a digital micrometer (Mutitoyo ±0.001 mm, Japan). Then, with/length ratios were calculated.

A Hunter Lab Scan Colorimeter (Hunter Lab Mini Scan XE, Hunter Associates Laboratory Inc., Reston, VA, U.S.A.) was used to measure color parameters (*L*, lightness/darkness; *a*, redness/greenness; *b*, yellowness/blueness) of dessert samples. Six random readings were taken from the outer and inner surfaces of each sample and an average of the three readings was taken for each surface. Outer color (shell) measurements were obtained by placing the instrument's measurement probe directly contact with the intact sample surface. For inner color analysis, the samples were sectioned horizontally, and measurements were taken from the geometric center of the cross-sectional surface. The instrument was calibrated before taking measurement with a standard white and black plates. These measurements were carried out in triplicate as described in Elgün *et al.* (2012).

Chemical properties and Mineral substance analysis

Dessert moisture contents were determined by gravimetric method in accordance with Association of American Analytical Chemists (AOAC, 2019). Both fat and ash contents (%) were determined as described by Elgün *et al.* (2012).

Dessert minerals were analyzed in a spectrometer (ICP-OES, Perkin Elmer, Optima 2100 DV, Massachusetts) as described by Göncü and Çelik (2020). About 0.5 g of each sample was dried at 70 °C and milled in blander, then supplemented with 6 ml of HNO3 and 2 ml of H2O2. The mixture was left to stand for 30 min and in microwave method of wet decomposition was fulfilled. Samples burnt in microwave were filtered through filter paper and B, P, K, Ca, Mg, Fe, Cu, Mn and Zn contents were determined in inductively coupled plasma optical emission spectrometry (ICP-OES, Perkin Elmer, Optima 2100 DV, Massachusetts, US). The ICP-OES system was set as follows; radio frequency (RF) power of 1.5 kW; plasma gas flow rate of 15 L min^{-1}; auxiliary gas flow rate of 0.2 L min^{-1}; nebulizer gas flow rate of 0.6 L min^{-1}; sample aspiration rate of 1.5 mL min^{-1}; delay time of 10 s; and ambient laboratory temperature of 24 °C.

Acrylamide and HMF analysis

Acrylamide content of dessert samples was assessed through the method outlined by Boyacı (2012), with slight modifications. First, the dessert samples were homogenized and ground into a fine mass/paste, and 10 g of each sample was precisely measured. The samples were defatted by adding 10 mL of hexane followed by stirring for 15 minutes. The suspension was subsequently filtered through coarse filter paper, allowing the residue to stand for 30 min to ensure thorough evaporation of the hexane. Next, 1 g of the defatted sample was taken for analysis. Then, 8.2 mL of distilled water that had been preheated to 60°C and 300 µL each of Carrez I and Carrez II solutions were added. The mixture was stirred for 20 min on a magnetic stirrer set at 60°C. After this, 2 mL of the extract was transferred to a centrifuge tube, rinsed with distilled water, and centrifuged at 5000 rpm for 30 min. The supernatant was then collected and filtered through a 0.45 µm membrane filter. For the derivatization process, 3 mL of the filtered extract was combined with 300 µL of a bromination solution, which was made from bromine water (5 mL), potassium bromide (15.2 g), hydrobromic acid (0.8 mL), and ultrapure water (60 mL). The samples were wrapped in aluminum foil and placed in an ice bath for 1 hour. To stop the reaction, several drops of a 1 M sodium thiosulfate solution were introduced. After this, 2 mL of ethyl acetate was incorporated, and the mixture was shaken for 30 seconds before being centrifuged at 5000 rpm for 10 min. The resulting upper organic layer was transferred into vials for GC–MS analysis, with triethylamine added in a volume that corresponded to 10% of the vial's sample volume. Acrylamide analysis was conducted using a GC–MS system (Agilent Technologies, California, USA) fitted with a DB-WAX capillary column (30 m × 0.25 mm × 0.25 µm; J&W Scientific, USA). The temperatures for the injector, detector, and ion source were set at 240°C, 250°C, and 230°C, respectively. Injections were performed in splitless mode with an injection volume of 2 µL. The temperature program for the oven was as follows: the initial temperature of 50°C held for 1 min, increased by 20°C/min to 180°C, then by 10°C/min to 230°C (held for 20 min), and lastly increased by 10°C/min to 260°C (held for 10 min). Helium served as the carrier gas at a flow rate of 1 mL/min. Detection was carried out in selected ion monitoring (SIM) mode, utilizing m/z 71 as the reference ion. Acrylamide concentrations were quantified using external calibration curves created with reference standards ranging from 0.01 to 500 mg/kg.

The analysis of HMF was performed using high-performance liquid chromatography (HPLC) from Agilent Technologies, California, USA. First, 6.9 g of each sample was measured and diluted to a total volume of 50 mL with distilled water. The resulting solution was then passed through a 0.45 µm syringe membrane filter to eliminate any particulate impurities before analysis. The filtered samples were then injected into the HPLC apparatus. The quantification of HMF was conducted using an external calibration curve created with standard HMF solutions at various concentrations. The mobile phase was composed of distilled water and methanol in a ratio of 80:20 (v/v) and was pumped at a flow rate of 1 mL/min. Chromatographic separation took place at room temperature using a C18 column (150 × 4.6 mm, with a 3 µm particle size), with detection performed by a diode array detector (DAD) at a wavelength of 285 nm, following the method outlined in Koç *et al*. (2011).

Statistical analysis

The data of the study were analyzed using SPSS statistical software. One-way ANOVA and Welch's t-test were performed to evaluate the effects of dessert type, supply source (Patisserie vs Vendor), and district on the measured parameters. Correlations between physical/chemical parameters and HMF and acrylamide levels were evaluated using Spearman's rank correlation coefficient (Spearman's rho, ρ). Statistical significance was accepted at ($p < 0.05$). Principal component analysis (PCA), heat map and cluster analyses were performed using JMP-Pro statistical software to elucidate the relationships among the measured traits of the samples. All analyses were carried out in triplicate and results were expressed as mean ± standard deviation. Different superscript letters indicate statistically significant differences ($p < 0.05$), where superscript ([a]) denotes supply-source effects and superscript ([b]) denotes district effects.

Results and discussion

Physical properties and color parameters of desserts

Desserts vary in texture based on factors like size, shape and ingredients (e.g. flour can be tapioca, rice or arrowroot flour; egg yolks can be from duck or chicken), as well as concentrations of sugar solution and sweeteners (Promsakhana Sakon Nakhon *et al.*, 2023a). As reported in Table 1 (Physical parameters) and Table 2 (color), the physical properties of the dessert samples were compared across supply source (Patisserie vs Vendor) and district (Efeler, Nazilli, Söke, Kuşadası, Didim), and values were presented as mean ± standard deviation. As reported in Table 1, the physical properties of dessert samples were compared across supply source (Patisserie vs Vendor) and district (Efeler, Nazilli, Söke, Kuşadası, Didim), and values were presented as mean ± standard deviation. Overall, the findings indicate that physical characteristics varied significantly by both supply chain and geographic context, although the magnitude and pattern of variation depend strongly on dessert type and parameter.

In Şambali, marked differences were observed across multiple geometric and color-related attributes; notably, width and outer color coordinates (L_outer, b_outer) frequently exhibited combined supply and district effects ([ab]), while length and diameter/height were largely influenced by district variability ([b]) in patisserie samples. In the vendor-sourced Şambali samples, district effects were evident for several dimensional indices and inner color components (e.g., a_inner, b_inner), suggesting that shaping consistency and production practices vary across locations.

For Halka, significant effects were consistently detected for color and shape indices: several parameters showed strong supply-related differences ([a])in specific districts (e.g., width in Söke and Kuşadası vendor samples, and width in Söke and

Kuşadası patisserie samples), while district-related variability ([b]) was frequently observed for length, diameter/height, and width/length ratio in patisserie products. Notably, repeated ([ab]) markings for color coordinates (both outer and inner L, a, b) indicate that both the point of supply and district-specific production conditions contribute to surface color differences in Halka.

In Lokma, highly significant variability was mainly associated with dimensional properties, as several districts exhibited combined effects ([ab]) in width, length, and diameter/height (particularly in Söke and Kuşadası), indicating that Lokma samples are sensitive to both supply conditions and local production styles. In addition, color parameters (especially L_outer and b_inner) frequently displayed district effects ([b]) and/or combined effects ([ab]), supporting the conclusion that color development during frying is influenced by both process control and district-dependent practices. This color change by types is caused by the chemical properties of ingredients, differences of process that readily undergoes the Maillard reaction at elevated temperatures. This corroborates with data from other studies who reported that color parameters of Turkish syrup desserts varied with the protein source, flour type, frying conditions and ingredients (Özen *et al.*, 2009; Yıldırım *et al.*, 2018; Seyyedcheraghi *et al.*, 2023). Present findings also comply with the results of Çelik and Kuzumoğlu (2020) who reported higher lightness (51.56) and lower redness (3.49) and yellowness (19.36) values for the crust of Lokma desserts.

Collectively, Table 1 demonstrates that physical attributes of traditional desserts are not constant across the supply chain; instead, significant supply-related differences (reflecting standardization and shaping consistency) and district-related variability (reflecting local processing practices) jointly contribute to the observed heterogeneity in product geometry and color (Table 2). It is possible that the differences in shapes changed the size of desserts since Lokma is small and sphere, Halka has serration and ring and Şambali is rectangular. Similar to the present study, the lokma samples exercised similar diameter levels ranging from 33.15 to 33.58 (Çelik and Tümer, 2020). Complying with the present findings, Çelik and Kuzumoğlu (2020) reported width/length ratios as between 1.10 - 1.18. Moreover, Yildiz and Bulut (2016) reported lengths of Tulumba desserts as between 3.0 - 3.5 cm and diameters as between 1.87 - 2.74 cm. Reductions in sugar quantities of syrup resulted in a significant increase in both the size and expansion ratio of sweet egg yolk desserts, but their bulk density decreased as well (Promsakhana Sakon Nakhon *et al.*, 2023a). Replacing sucrose with different sweeteners led to a decrease in the size of low-sugar egg-based syrup desserts (Promsakhana Sakon Nakhon *et al.*, 2023b). It was discovered that adding flaxseed flour to cookies increased their thickness and decreased their volume expansion (Kaur *et al.*, 2019).

Table 1. Physical properties of dessert samples

Desert	Place of supply	Locations	Width (mm)	Length (mm)	Diameter (Height, mm)	Width/ Length
Şambali	Patisserie	Efeler	32.53±3.38 [ab]	96.33±13.56 [b]	30.33±5.50 [b]	0.35±0.09 [b]
		Nazilli	34.02±3.95 [ab]	80.58±6.04 [ab]	30.30±2.70 [ab]	0.42±0.03 [ab]
		Söke	33.17±1.94 [b]	79.83±6.43 [ab]	35.00±0.89 [ab]	0.42±0.03 [ab]
		Kuşadası	30.50±1.38 [b]	90.00±2.76 [b]	34.17±3.19 [ab]	0.34±0.03 [b]
		Didim	28.00±5.48 [b]	101.33±12.42 [b]	29.67±2.25 [ab]	0.27±0.02 [b]
	Vendor	Efeler	29.51±2.59 [a]	82.84±19.28	32.60±3.13 [b]	0.37±0.09
		Nazilli	28.00±1.00 [a]	103.00±0.00 [a]	32.33±0.58 [ab]	0.27±0.01 [a]
		Söke	31.18±3.93	100.78±0.90 [a]	32.02±2.34 [ab]	0.31±0.04 [a]
		Kuşadası	28.49±6.69	82.37±12.21	29.29±4.17 [ab]	0.36±0.13
		Didim	33.33±0.82	83.00±34.39	35.50±1.64 [ab]	0.69±0.85
Halka	Patisserie	Efeler	95.67±34.47	97.13±32.38 [b]	25.27±3.92 [b]	0.97±0.09 [b]
		Nazilli	99.19±9.36	115.72±12.44 [b]	21.92±3.09 [ab]	0.87±0.15 [ab]
		Söke	95.78±6.98 [a]	123.78±12.19 [b]	27.11±4.65 [b]	0.78±0.07 [ab]
		Kuşadası	108.44±5.36 [a]	117.89±4.94 [ab]	21.33±0.71 [ab]	0.92±0.02 [ab]
		Didim	101.67±9.87	121.17±11.87 [b]	22.67±0.82 [ab]	0.84±0.01 [b]
	Vendor	Efeler	99.34±34.52	103.92±35.47	25.72±4.33	0.95±0.05 [b]
		Nazilli	81.11±42.37	113.11±48.16	27.60±5.14 [a]	0.71±0.18 [ab]
		Söke	120.50±0.37 [a]	119.24±0.07	23.58±1.53	1.01±0.00 [ab]
		Kuşadası	90.52±0.15 [a]	125.90±0.31 [a]	24.95±1.03 [a]	0.72±0.00 [ab]
		Didim	103.67±0.58	124.33±1.15	20.00±1.00 [a]	0.83±0.01 [b]
Lokma	Patisserie	Efeler	63.49±10.69 [b]	62.18±9.91 [b]	24.84±4.42 [b]	1.02±0.04 [b]
		Nazilli	52.55±4.34 [b]	54.09±2.93 [b]	19.58±4.09 [b]	0.97±0.05 [b]
		Söke	45.19±0.29 [ab]	54.28±0.41 [ab]	15.67±0.59 [ab]	0.83±0.00 [ab]
		Kuşadası	30.00±0.00 [ab]	35.00±1.00 [ab]	32.33±0.58 [ab]	0.86±0.02 [ab]
	Vendor	Efeler	49.46±28.87	48.36±32.01	23.02±5.26	1.09±0.28
		Söke	33.05±11.49 [a]	36.05±15.50 [a]	21.46±4.22 [a]	0.94±0.08 [a]
		Kuşadası	46.28±12.02 [a]	48.09±12.65 [a]	21.98±5.05 [a]	0.96±0.02 [a]
		Didim	26.33±2.96	26.42±0.63	22.50±1.38	1.00±0.11

Note: Superscripts indicate significance tests:

[a] = Supply source effect (Patisserie vs Vendor) within the same dessert and district (Welch t-test)

[b] = District effect (between districts) within the same dessert and supply source (one-way ANOVA), Significance levels: $p < 0.05$

Table 2. Color values of dessert samples.

Desert	Place of supply	Locations	Hunter Lab Values L outer	a outer	b outer	L inner	a inner	b inner
Şambali	Patisserie	Efeler	35.09±1.89 ^{ab}	38.04±1.83	21.68±4.70 ^{ab}	4.92±2.51	12.67±5.73	18.10±1.55 ^{a}
		Nazilli	33.20±2.14 ^{ab}	41.70±12.64	14.68±4.47 ^{ab}	7.47±8.19	15.37±6.38	18.28±18.96
		Söke	34.65±5.01 ^{ab}	43.48±0.65	11.25±4.26 ^{b}	4.23±0.26 ^{a}	14.56±9.51 ^{a}	14.83±6.91 ^{a}
		Kuşadası	39.42±0.82 ^{ab}	37.34±0.87 ^{a}	22.87±9.77 ^{ab}	8.61±3.66	18.33±4.10	19.91±0.63 ^{a}
		Didim	35.90±0.53 ^{b}	39.15±0.75	21.47±3.21 ^{b}	4.20±0.69	15.05±3.25	19.50±0.53 ^{a}
	Vendor	Efeler	24.77±11.84 ^{ab}	38.32±1.71 ^{b}	15.39±4.29 ^{ab}	6.72±2.20 ^{b}	14.70±3.94 ^{b}	27.23±9.43 ^{ab}
		Nazilli	36.34±0.06 ^{ab}	40.22±0.19 ^{b}	24.70±0.20 ^{ab}	3.46±0.12 ^{b}	15.45±0.13 ^{b}	19.10±0.09 ^{b}
		Söke	18.90±0.14 ^{ab}	39.27±5.46 ^{b}	15.67±0.54 ^{b}	7.41±2.15 ^{ab}	25.63±2.70 ^{ab}	37.98±1.97 ^{ab}
		Kuşadası	16.59±1.40 ^{ab}	33.96±1.81 ^{ab}	12.48±0.90 ^{ab}	8.14±3.62 ^{b}	17.82±1.27 ^{b}	29.88±5.29 ^{ab}
		Didim	35.93±3.67 ^{b}	41.34±5.36 ^{b}	19.22±4.39 ^{b}	4.31±1.89 ^{b}	18.88±4.03 ^{b}	14.42±3.64 ^{ab}
Halka	Patisserie	Efeler	34.61±1.46 ^{a}	41.17±2.57 ^{b}	20.22±7.05 ^{ab}	1.85±0.80 ^{a}	15.02±3.35 ^{ab}	11.04±2.03 ^{ab}
		Nazilli	35.96±2.12 ^{a}	51.07±7.50 ^{ab}	12.82±5.01 ^{b}	3.36±2.95	18.11±2.06 ^{ab}	17.96±4.06 ^{b}
		Söke	35.30±3.41 ^{a}	44.53±2.87 ^{ab}	13.85±4.82 ^{b}	3.00±1.92	18.70±4.13 ^{b}	12.77±0.76 ^{ab}
		Kuşadası	33.16±5.04 ^{a}	39.74±5.40 ^{b}	14.84±4.03 ^{b}	4.92±3.29 ^{a}	15.26±3.93 ^{ab}	14.54±2.00 ^{ab}
		Didim	34.09±3.27 ^{a}	46.70±3.17 ^{ab}	27.41±1.65 ^{ab}	3.03±3.02	12.94±1.08 ^{ab}	14.70±1.76 ^{ab}
	Vendor	Efeler	26.29±5.96 ^{ab}	40.51±4.38 ^{b}	13.18±1.96 ^{ab}	2.67±0.86 ^{ab}	19.22±4.93 ^{ab}	23.25±8.58 ^{ab}
		Nazilli	30.23±7.20 ^{ab}	44.62±5.58 ^{ab}	14.65±3.35 ^{b}	3.87±1.91 ^{b}	21.12±3.38 ^{ab}	21.36±7.69 ^{b}
		Söke	22.22±0.04 ^{ab}	40.73±0.08 ^{ab}	13.10±0.02 ^{b}	2.24±0.01 ^{b}	20.47±0.10 ^{b}	27.03±0.03 ^{ab}
		Kuşadası	22.01±0.13 ^{ab}	37.40±0.05 ^{b}	14.87±0.02 ^{b}	2.30±0.03 ^{ab}	23.61±0.04 ^{ab}	24.63±0.03 ^{ab}
		Didim	16.12±0.67 ^{ab}	33.37±0.29 ^{ab}	18.57±0.21 ^{ab}	4.48±0.02 ^{b}	10.65±0.19 ^{ab}	9.37±0.19 ^{ab}
Lokma	Patisserie	Efeler	32.61±5.89	43.40±3.39 ^{ab}	11.50±2.73	1.84±1.55	28.08±1.63 ^{ab}	21.02±4.91
		Nazilli	42.62±9.99	56.51±8.84 ^{b}	9.30±2.46	1.80±0.25	23.59±0.36 ^{b}	18.30±4.88
		Söke	36.93±0.04 ^{a}	45.47±0.07 ^{b}	8.60±0.01 ^{a}	1.59±0.02	26.98±0.04 ^{ab}	20.17±0.05 ^{a}
		Kuşadası	34.47±0.60 ^{a}	55.61±0.37 ^{ab}	11.57±0.44	3.43±0.09 ^{a}	14.96±1.34 ^{ab}	14.80±0.40 ^{a}
	Vendor	Efeler	37.10±10.07 ^{b}	52.25±10.35 ^{ab}	14.07±7.98	1.87±1.03 ^{b}	24.77±4.86 ^{a}	17.49±2.82 ^{b}
		Söke	27.05±2.57 ^{ab}	45.57±2.48 ^{b}	12.24±1.40 ^{a}	1.41±0.72 ^{b}	23.51±1.29 ^{a}	17.84±1.56 ^{ab}
		Kuşadası	26.71±2.56 ^{ab}	48.97±1.58 ^{ab}	11.99±1.11	2.34±1.06 ^{ab}	23.29±3.30 ^{a}	21.94±4.29 ^{ab}
		Didim	29.69±3.27 ^{b}	44.18±1.70 ^{b}	9.85±2.27	1.04±0.03 ^{b}	24.01±1.22	18.14±0.44 ^{b}

Note: Superscripts indicate significance tests:
^{a} = Supply source effect (Patisserie vs Vendor) within the same dessert and district (Welch t-test)
^{b} = District effect (between districts) within the same dessert and supply source (one-way ANOVA), Significance levels: $p < 0.05$

Chemical properties of desserts and mineral matters

As presented in Table 3 and Table 4, the chemical composition parameters of the dessert samples (moisture, ash, fat and selected mineral elements) were evaluated with respect to both supply source (Patisserie vs Vendor) and district (Efeler, Nazilli, Söke, Kuşadası, Didim). Overall, the findings demonstrate that chemical composition variability may be explained by both dimensions of variation, depending on the dessert type and parameter.

For Şambali, several variables exhibited significant supply-related differences, including Fe (mg/kg) in Efeler, moisture (%) in Nazilli, and K (mg/kg) and P (mg/kg) in Söke, , indicating that Patisserie and Vendor samples can differ even under the same district conditions. In addition, fat (%) in Kuşadası showed a significant supply-source effect. District-related variation was also evident within the Şambali Vendor group, particularly for ash (%) and fat (%), and for Mg (mg/kg), suggesting that location-dependent production conditions may influence composition even within the same supply category.

For Halka, the most prominent pattern was the consistent presence of significant district effects on moisture content, observed in both Patisserie and Vendor samples ([b]). Moreover, in Söke, Kuşadası and Didim, moisture values exhibited combined supply and district effects ([ab]) in the Patisserie group, implying that both sourcing and location may simultaneously contribute to variation in this parameter. Additionally, Halka samples showed a significant supply effect on fat (%) in Kuşadası, and on ash (%) in Didim.

For Lokma, significant differences were mainly associated with district-related variability in ash (%) and fat (%), particularly within the Patisserie group ([b]), while combined effects ([ab])were detected in Söke and Kuşadası for ash and fat.

Obtained results indicate that dessert composition is not solely determined by product type, but may vary significantly according to supply-chain-related differences (Patisserie vs Vendor) and district-level variability, with the magnitude and relevance of these effects depending on the specific chemical parameter assessed. Çelik and Tümer (2020) reported similar moisture contents for Lokma desserts (20.56 - 24.66%), but higher ash contents (0.764 - 0.818%) and mineral levels and lower fat contents (11.00 - 11.29%). The different physicochemical characteristics (for example, minerals, ash, fat) of Lokma desserts could be related to barley and wheat kavurga flour used as substitutes of wheat flour. In the study conducted by Çelik and Kuzumoğlu (2020), gluten-free control Lokma desserts with grape seed powder, flaxseed flour and melon seed powder exercised moisture of 21%, fat of 38.64% and ash of 0.66 %. Similarly, chemical composition of desserts was dependent upon the ingredients and varieties. Because the precise formulation and processing factors are unknown, discussing the variations in composition parameters is difficult.

Acrylamide and HMF analysis

As shown in Table 4, the variability of HMF and acrylamide concentrations in dessert samples was evaluated with respect to both supply source (Patisserie vs Vendor) and district (Efeler, Nazilli, Söke, Kuşadası, Didim). Overall, Table 3 demonstrates that significant differences may arise from both dimensions of variation: several dessert–district combinations exhibit ([a]) significance across $p<0.05$ levels, indicating that products obtained from patisseries and street vendors can differ substantially in terms of HMF and acrylamide concentrations even within the same district. At the same time, district-related differences ([b]) were also observed in multiple dessert–supply subsets, suggesting that district-specific processing and production conditions may contribute to the measured variability across locations. The lowest and highest acrylamide contents of street vendor samples were 179.90 and 484.92 µg/kg. The major acrylamide content came from Şambali and Halka samples of patisserie located in Söke and Kuşadası districts. Given that acrylamide formation is governed by the interaction of free asparagine and reducing sugars—whose levels differ between semolina- and wheat flour–based matrices—and is further promoted under high-temperature, low-moisture frying conditions, differences in formulation and processing are key determinants of contaminant levels. The different types of desserts shared a similar concentration distribution for HMF contents. Additionally, Halka had a large distribution variance, exactly reflecting the large heterogeneity in the street vendors located in Efeler districts of Aydın province. Moreover, although there is currently no specific regulatory limit for acrylamide in traditional desserts in Türkiye, the results were interpreted in relation to a 300 µg/kg benchmark level commonly applied to comparable carbohydrate-rich food categories. In this context, Table 3 shows that several dessert–district–supply combinations exhibit mean acrylamide concentrations exceeding 300 µg/kg, highlighting relevant groups for risk-oriented evaluation and potential mitigation. Notably, higher mean acrylamide values were frequently observed in Patisserie-sourced samples, particularly for Şambali and Halka collected in Kuşadası and Söke, while elevated HMF means were more pronounced in certain Vendor samples, especially among Lokma in specific districts (e.g., Didim). Present findings revealed that patisserie samples contained important levels of acrylamide and street vendor samples had risky levels of HMF. Therefore, HMF and acrylamide concentrations of desserts sold in street vendors and patisserie could pose potential health risks on public health, international tourists as well as traditional Turkish dessert consumers. It is well known that street vending can contribute to congestion and health and safety risks in cities and street vendors may operate in fixed premises or use mobile stalls (Anaafo *et al.*, 2024). Moreover, the highest content of acrylamide was detected in potato chips from unorganized food processing units in India (Muthaiah *et al.*, 2019)

Table 3. Mineral composition of dessert samples according to supply source and district.

Desert	Place of supply	Locations	Minerals B (mg/kg)	Ca (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	K (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	P (mg/kg)	Zn (mg/kg)
Şambali	Patisserie	Efeler	0.32±0.28	300±0.02	1.06±0.11	41.81±14.95 [a]	900±0.03	200±0.00	3.95±0.58	1000±0.03	6.23±1.43
		Nazilli	0.16±0.07	300±0.01	1.26±0.33	33.86±10.72	1000±0.01	200±0.00	4.34±1.35	800±0.01	6.62±1.63
		Söke	0.28±0.01	400±0.01	1.04±0.03	51.65±29.03	1300±0.01 [a]	300±0.01	3.89±0.16	1300±0.01 [a]	6.59±0.41
		Kuşadası	1.11±0.77	200±0.01	1.21±0.41	57.95±15.83	1100±0.00	400±0.02	3.87±1.39	1000±0.05	6.76±2.56
		Didim	0.30±0.28	300±0.01	1.73±0.47	146.27±111.56	1000±0.02	400±0.01	6.19±2.08	900±0.03	10.10±2.95
	Vendor	Efeler	0.21±0.06	300±0.03	1.07±0.10	17.39±3.18 [a]	900±0.01	200±0.00 [b]	4.54±0.52	800±0.03	7.61±1.91
		Nazilli	0.26±0.00	200±0.00	1.20±0.00	51.67±0.00	700±0.00	200±0.00 [b]	3.78±0.00	600±0.00	8.44±0.00
		Söke	0.20±0.08	200±0.00	0.77±0.22	17.00±5.69	600±0.01 [a]	100±0.00 [b]	2.72±0.86	600±0.01 [a]	6.04±1.29
		Kuşadası	0.31±0.18	200±0.00	1.01±0.32	18.14±2.76	900±0.03	300±0.00 [b]	4.65±1.78	700±0.01	7.36±2.66
		Didim	0.17±0.05	100±0.01	1.14±0.27	87.44±59.00	800±0.04	300±0.01 [b]	5.10±2.17	800±0.01	8.35±4.41
Halka	Patisserie	Efeler	1.03±2.13	200±0.01	1.18±0.19	34.02±19.03	1100±0.04	300±0.03	4.45±0.60	900±0.04	8.74±4.51
		Nazilli	0.09±0.04	200±0.00	1.19±0.15	28.24±13.09	900±0.02	200±0.01	4.89±1.54	800±0.01	7.78±1.93
		Söke	0.21±0.19	300±0.01	0.95±0.20	44.00±7.29	900±0.03	200±0.01	3.10±1.06	700±0.04	5.54±0.97
		Kuşadası	0.23±0.13	300±0.03	1.03±0.32	48.20±29.53	800±0.03	300±0.01	4.15±2.10	800±0.04	6.41±2.59
		Didim	2.04±2.76	700±0.07	1.55±0.57	35.67±15.39	1000±0.03	400±0.01	5.71±0.25	1400±0.10	9.72±3.37
	Vendor	Efeler	0.24±0.01	300±0.00	1.22±0.33	44.41±28.37	800±0.02	200±0.01	5.31±0.85	800±0.02	8.85±2.14
		Nazilli	0.19±0.10	300±0.01	1.19±0.22	32.34±14.35	900±0.01	200±0.00	4.69±0.74	800±0.01	8.26±1.38
		Söke	0.27±0.00	300±0.00	1.04±0.00	18.73±0.00	900±0.00	200±0.00	5.53±0.00	800±0.00	6.54±0.00
		Kuşadası	0.21±0.00	500±0.00	0.76±0.00	11.94±0.00	900±0.00	200±0.00	3.13±0.00	700±0.00	5.70±0.00
		Didim	0.17±0.00	200±0.00	1.27±0.00	51.38±0.00	1200±0.00	300±0.00	5.13±0.00	900±0.00	9.74±0.00
Lokma	Patisserie	Efeler	0.24±0.15	200±0.01	1.31±0.12	15.26±6.64	800±0.03	200±0.01	4.62±2.04	700±0.03	6.46±2.67
		Nazilli	0.16±0.17	200±0.01	1.07±0.41	24.48±17.03	900±0.02	200±0.01	4.13±1.47	700±0.03	7.08±2.58
		Söke	0.19±0.00	200±0.00	1.03±0.00	23.93±0.00	800±0.00	200±0.00	5.22±0.00	600±0.00	7.48±0.00
		Kuşadası	0.18±0.00	300±0.00	0.96±0.00	36.59±0.00	1100±0.00	200±0.00	4.19±0.00	800±0.00	6.71±0.00
	Vendor	Efeler	0.26±0.16	200±0.00	1.44±0.23	28.36±14.85	900±0.02	300±0.00	5.52±1.22	900±0.02	8.36±2.22
		Söke	0.18±0.16	300±0.01	1.16±0.32	19.79±8.22	800±0.01	300±0.01	4.21±1.40	800±0.02	8.47±2.58
		Kuşadası	0.14±0.19	200±0.01	1.17±0.40	16.16±6.88	1000±0.03	200±0.01	4.58±1.64	800±0.02	8.16±3.40
		Didim	0.27±0.08	200±0.00	0.75±0.09	26.73±11.11	600±0.01	200±0.00	3.27±0.01	500±0.00	4.39±0.74

Note: Superscripts indicate significance tests:

[a] = Supply source effect (Patisserie vs Vendor) within the same dessert and district (Welch t-test)

[b] = District effect (between districts) within the same dessert and supply source (one-way ANOVA), Significance levels: $p < 0.05$,

B: Boron; Ca: Calcium, Cu: Copper; Fe: Iron; K: Potassium, Mg: Magnesium, Mn: Manganese, P: Phosphorus, Zn: Zinc n.d.: not detected.

Table 4. Chemical properties, Acrylamide and HMF concentrations of dessert samples according to supply source and district.

Desert	Place of supply	Locations	Moisture (%)	Ash (%)	Fat (%)	HMF (mg/kg) Mean	Acrylamide (µg/kg) Mean
Şambali	Patisserie	Efeler	29.44±3.75	0.47±0.11	12.83±0.75	1.44±3.04	375.94±78.01 ^{ab}
		Nazilli	27.59±1.41 ^{a}	0.40±0.15	12.72±0.78	1.72±3.18 ^{a}	395.04±81.46 ^{ab}
		Söke	25.39±1.66	0.60±0.08	13.19±2.77	3.98±4.59	467.80±35.21 ^{ab}
		Kuşadası	27.07±0.86	0.45±0.11	12.33±1.46 ^{a}	0.00±0.00 ^{a}	497.61±73.19 ^{ab}
		Didim	26.21±1.32	0.52±0.01	13.36±1.33	3.96±4.57	325.34±85.38 ^{b}
	Vendor	Efeler	27.64±1.93	0.47±0.05 ^{b}	13.59±0.94 ^{b}	4.82±5.16	252.70±66.88 ^{a}
		Nazilli	26.34±0.18 ^{a}	0.42±0.00 ^{b}	13.86±0.39 ^{b}	7.10±0.11 ^{a}	260.49±1.02 ^{a}
		Söke	26.76±1.04	0.58±0.04 ^{b}	14.10±0.14 ^{b}	8.57±0.65	326.24±23.59 ^{a}
		Kuşadası	26.54±1.26	0.62±0.07 ^{b}	15.28±0.35 ^{ab}	10.99±3.23 ^{a}	267.32±10.56 ^{a}
		Didim	27.63±1.07	0.52±0.01 ^{b}	15.65±1.70 ^{b}	7.61±1.09	258.60±27.92
Halka	Patisserie	Efeler	25.19±0.99 ^{b}	0.46±0.08	15.71±2.50	6.05±3.24 ^{a}	403.08±34.67 ^{ab}
		Nazilli	24.46±0.69 ^{b}	0.46±0.08	14.74±2.52	5.81±4.59 ^{a}	322.84±75.01 ^{b}
		Söke	23.35±0.81 ^{ab}	0.37±0.18	14.50±2.16	7.64±5.96	448.50±101.39 ^{ab}
		Kuşadası	24.13±1.13 ^{ab}	0.28±0.13	14.59±0.49 ^{a}	11.28±2.50 ^{a}	493.19±40.57 ^{ab}
		Didim	23.57±0.57 ^{ab}	0.37±0.15 ^{a}	15.58±2.19	11.10±3.55	354.28±115.99 ^{b}
	Vendor	Efeler	24.57±0.41 ^{b}	0.42±0.18	14.07±1.09	18.62±16.65 ^{a}	268.31±27.06 ^{ab}
		Nazilli	25.11±1.69 ^{b}	0.48±0.06	13.65±1.59	13.88±7.95 ^{a}	302.48±47.66 ^{b}
		Söke	24.61±0.31 ^{ab}	0.53±0.01	13.93±0.01	6.78±0.01	226.98±5.75 ^{ab}
		Kuşadası	26.34±0.43 ^{ab}	0.30±0.00	16.09±0.11 ^{a}	15.90±0.21 ^{a}	275.27±17.08 ^{ab}
		Didim	22.57±0.37 ^{b}	0.62±0.01 ^{a}	13.06±0.32	8.51±0.06	226.97±14.55 ^{b}
Lokma	Patisserie	Efeler	23.06±1.10	0.23±0.05 ^{b}	13.63±0.65 ^{b}	7.53±1.02 ^{b}	327.63±55.59
		Nazilli	23.55±1.19	0.21±0.07 ^{b}	15.86±0.97 ^{b}	2.26±3.49 ^{b}	363.75±66.49
		Söke	22.09±0.50	0.28±0.00 ^{ab}	15.39±0.06 ^{b}	7.90±0.39 ^{b}	301.84±7.51
		Kuşadası	22.45±0.47	0.37±0.00 ^{ab}	14.42±0.13 ^{ab}	16.94±0.62 ^{ab}	217.76±53.55
	Vendor	Efeler	22.05±1.54	0.29±0.10	14.05±0.92 ^{b}	8.23±11.92 ^{b}	317.11±67.49
		Söke	22.73±1.90	0.22±0.01 ^{a}	14.95±0.45 ^{b}	7.21±1.40 ^{b}	279.36±5.48
		Kuşadası	21.52±0.94	0.23±0.01 ^{a}	13.62±0.23 ^{ab}	6.83±6.37 ^{ab}	286.46±61.48
		Didim	22.11±0.56	0.31±0.03	13.93±0.65 ^{b}	27.95±1.02 ^{b}	294.89±55.37

Note: Superscripts indicate significance tests:

^{a} = Supply source effect (Patisserie vs Vendor) within the same dessert and district (Welch t-test)

^{b} = District effect (between districts) within the same dessert and supply source (one-way ANOVA)

Significance levels: $p < 0.05$.

Overall, these findings indicate that HMF and acrylamide formation is influenced by a combination of supply-chain-related factors (e.g., thermal processing conditions, oil quality and reuse practices, and degree of standardization) and district-level variability, both of which can shape contaminant levels depending on dessert type and sampling context. The variation among the types is related to differences in composition and processing methods among various places and types of desserts, as acrylamide and HMF formation is directly influenced by these factors. Since the formulation was not known completely, it is not possible to discuss the impacts of specific ingredients. Şambali is composed primarily of semolina, sugar, yogurt, and leavening agents and is baking, whereas Halka and Lokma are wheat flour–based dough products processed by deep-fat frying and subsequently immersed in sugar syrup. These differences in cereal based products, formulation and processing conditions are critical factors of acrylamide formation, as free asparagine and reducing sugars constitute the principal precursors, their levels vary between semolina and wheat flour matrices. Furthermore, the higher temperatures and lower moisture levels associated with frying may increase acrylamide generation compared with baking. Complying with the present findings, the highest levels of the acrylamide contaminant were also found in Kemalpaşa (512 µg/kg) and Tulumba (241 µg/kg) obtained from the Turkish markets (Ölmez *et al.*, 2008). However, the roughly three times lower acrylamide content was observed in Baklava (25 and 154 µg/kg), Halka (75 and 115 µg/kg), Lokma (111 µg/kg) and Tulumba (81 and 132 µg/kg) (Özer *et al.*, 2012). A lower variation was observed in the acrylamide content of these traditional desserts, which can be attributed to the controlled conditions such as raw material composition, sugar content, food product formulations, processing methods and parameters. However, present HMF contents were highly lower than traditional Turkish Dibek coffees (47.16 mg kg^{-1} to 242.25 mg kg^{-1}), but similar to grape pekmez (1.33 to 13.4 mg kg^{-1}) (Akgün and Arıcı, 2019; Başaran *et al.*, 2021).

Correlation analysis between physicochemical parameters, HMF and acrylamide

In this study, associations between physical/chemical parameters and HMF and acrylamide levels were evaluated using Spearman’s rank correlation coefficient (Spearman’s rho, ρ) and provided in Table 5 and Table 6. No studies have been done on the relationships between some associated parameters, acrylamide and HMF levels of Şambali, Halka and Lokma desserts. Thus, present findings were compared to similar research conducted on other traditional Turkish desserts. HMF showed a significant moderate negative correlation with outer surface lightness (L outer*) ($\rho = -0.441$; $p < 0.001$), indicating that increased HMF levels were accompanied by decreased lightness and enhanced surface browning. No significant correlations were observed between HMF and geometric parameters (width, length, diameter). Acrylamide exhibited no significant relationships with most physical variables; however, a weak but significant positive correlation was found with L outer* ($\rho = 0.242$; $p = 0.033$). In addition, HMF and acrylamide were not significantly correlated ($\rho = -0.179$; $p = 0.116$), suggesting that these heat-related compounds may not increase simultaneously under the studied conditions.

Regarding chemical composition, HMF was significantly and negatively correlated with K (%) ($\rho = -0.242$; $p = 0.032$). Acrylamide showed significant associations with trace elements, being positively correlated with Fe (mg/kg) ($\rho = 0.236$; $p = 0.037$) and negatively correlated with Mn (mg/kg) ($\rho = -0.311$; $p = 0.006$) and Zn (%) ($\rho = -0.278$; $p = 0.014$). Overall, the findings suggest that HMF is more closely linked to browning-related physical quality changes, whereas acrylamide is more strongly associated with chemical matrix characteristics, particularly the trace element profile (Table 5 and Table 6). A moderate negative linear correlation was reported between color parameters *(*, a, b*) and acrylamide values of Pekmez and insignificant relationships were reported between acrylamide levels and color values (*L, a, b*) of Terebinth coffees ($p < 0.05$) (Akgün and Arıcı, 2019; Başaran *et al.,* 2021). The negative correlation of acrylamide with HMF is pretty surprising compared to the research in literature. HMF has a significant positive correlation with the formation of acrylamide in reconstituted potato chips (Miao *et al.,* 2014), Turkish coffee (Akgün and Arıcı, 2019) and pekmez (Başaran *et al.,* 2021). However, Alpözen and Üren (2013) stated that there was no significant correlation between acrylamide and HMF of a traditional Turkish bagel (İzmir Gevrek). Such differences with the literature could be attributed to several factors, such as composition, traditional processing methods and structure of food systems of Halka, Lokma and Şambali desserts. The formation of HMF and acrylamide is influenced by different factors. While colder temperatures and neutral or alkaline pH levels prevent the synthesis of HMF, higher temperatures and acidic conditions promote its formation (Jung *et al.,* 2021). Increased temperatures and longer cooking times lead to the formation of acrylamide, while acidic conditions and low moisture contents can boost its production (Zilić *et al.,* 2022). The Amadori product undergoes additional chemical transformations, this results in the formation of furan rings with HMF being one of the furan derivatives formed during this process (Shapla *et al.,* 2018). Lipinski *et al.* (2024) reported that furan formation could be more related to the process parameters than the grain type in breakfast cereals.

Table 5. Correlations of Acrylamide and HMF with physical parameters and color values in desserts.

Parameters	Width (mm)	Length (mm)	Diameter (Height)	Width/ Length	*L outer*	*L inner*	*a outer*	*a inner*	*b outer*	*b inner*	HMF (mg/kg)	Acrylamide (µg/kg)
Width (mm)	1.000											
Length (mm)	0.652 (0.000)	1.000										
Diameter (Height)	-0.445 (0.000)	0.030 (0.791)	1.000									
Width/Length	0.427 (0.000)	-0.272 (0.016)	-0.567 (0.000)	1.000								
L outer	0.060 (0.599)	0.041 (0.722)	-0.001 (0.991)	-0.004 (0.971)	1.000							
L inner	0.048 (0.678)	-0.321 (0.004)	-0.240 (0.035)	0.360 (0.001)	0.175 (0.125)	1.000						
a outer	0.074 (0.521)	0.434 (0.000)	0.317 (0.005)	-0.409 (0.000)	0.166 (0.146)	-0.191 (0.093)	1.000					
a inner	-0.184 (0.106)	0.238 (0.036)	0.436 (0.000)	-0.529 (0.000)	-0.018 (0.879)	-0.533 (0.000)	0.215 (0.058)	1.000				
b outer	-0.082 (0.474)	-0.412 (0.000)	-0.361 (0.001)	0.410 (0.000)	-0.044 (0.699)	0.355 (0.001)	-0.365 (0.001)	-0.301 (0.007)	1.000			
b inner	-0.244 (0.032)	-0.120 (0.294)	0.116 (0.311)	-0.237 (0.037)	-0.382 (0.001)	0.058 (0.616)	-0.043 (0.708)	0.180 (0.115)	0.435 (0.000)	1.000		
HMF (mg/kg)	0.056 (0.629)	0.086 (0.452)	0.021 (0.857)	0.123 (0.285)	**-0.441 (0.000)**	-0.026 (0.822)	-0.145 (0.206)	0.072 (0.532)	0.063 (0.585)	0.121 (0.291)	1.000	
Acrylamide (mg/kg)	0.078 (0.497)	0.106 (0.354)	0.065 (0.570)	-0.059 (0.609)	**0.242 (0.033)**	0.057 (0.619)	0.100 (0.383)	0.122 (0.287)	-0.103 (0.368)	-0.177 (0.121)	-0.179 (0.116)	1.000

Note: Correlation coefficients were calculated using Spearman's rank correlation (Spearman's rho, ρ). Values outside brackets represent correlation coefficients, while values within brackets represent p-values.

Table 6. Correlations of Acrylamide and HMF with chemical parameters and mineral content in desserts.

Parameters	Moisture (%)	Ash (%)	Fat (%)	B (mg/kg)	Ca (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	K (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	P (mg/kg)	Zn (mg/kg)	HMF (mg/kg)	Acrylamide (µg/kg)
Moisture (%)	1.000													
Ash (%)	0.447 (0.000)	1.000												
Fat (%)	-0.166 (0.147)	-0.149 (0.194)	1.000											
B (mg/kg)	0.003 (0.980)	0.096 (0.405)	-0.067 (0.559)	1.000										
Ca (mg/kg)	-0.173 (0.130)	0.095 (0.410)	-0.062 (0.587)	0.490 (0.000)	1.000									
Cu (mg/kg)	-0.162 (0.158)	0.052 (0.649)	-0.069 (0.550)	0.247 (0.029)	0.351 (0.002)	1.000								
Fe (mg/kg)	0.122 (0.285)	0.166 (0.147)	-0.012 (0.918)	0.075 (0.512)	0.073 (0.525)	0.091 (0.426)	1.000							
K (mg/kg)	-0.092 (0.425)	0.183 (0.109)	-0.145 (0.206)	0.359 (0.001)	0.515 (0.000)	0.511 (0.000)	0.270 (0.017)	1.000						
Mg (mg/kg)	-0.166 (0.146)	0.052 (0.654)	0.086 (0.455)	0.332 (0.003)	0.346 (0.002)	0.573 (0.000)	0.260 (0.021)	0.557 (0.000)	1.000					
Mn (mg/kg)	-0.223 (0.050)	0.128 (0.263)	-0.002 (0.985)	0.248 (0.029)	0.303 (0.007)	0.727 (0.000)	0.124 (0.281)	0.479 (0.000)	0.581 (0.000)	1.000				
P (mg/kg)	-0.030 (0.792)	0.202 (0.077)	-0.139 (0.226)	0.535 (0.000)	0.598 (0.000)	0.564 (0.000)	0.093 (0.419)	0.711 (0.000)	0.545 (0.000)	0.574 (0.000)	1.000			
Zn (mg/kg)	-0.161 (0.160)	0.175 (0.125)	0.016 (0.892)	0.335 (0.003)	0.466 (0.000)	0.760 (0.000)	0.136 (0.235)	0.544 (0.000)	0.624 (0.000)	0.833 (0.000)	0.652 (0.000)	1.000		
HMF (mg/kg)	-0.189 (0.097)	-0.002 (0.984)	0.176 (0.122)	-0.022 (0.850)	0.042 (0.712)	-0.139 (0.226)	-0.169 (0.140)	**-0.242 (0.032)**	-0.071 (0.539)	-0.090 (0.435)	-0.151 (0.186)	-0.019 (0.871)	1.000	
Acrylamide (mg/kg)	0.117 (0.307)	-0.100 (0.382)	0.024 (0.834)	0.030 (0.797)	-0.017 (0.880)	-0.116 (0.313)	**0.236 (0.037)**	0.184 (0.106)	-0.016 (0.893)	**-0.311 (0.006)**	0.058 (0.613)	**-0.278 (0.014)**	-0.179 (0.116)	1.000

Note: Correlation coefficients were calculated using Spearman's rank correlation (Spearman's rho, ρ).

Values outside brackets represent correlation coefficients, while values within brackets represent p-values.

B: Boron; Ca: Calcium, Cu: Copper; Fe: Iron; K: Potassium, Mg: Magnesium, Mn: Manganese, P: Phosphorus, Zn: Zinc.

Principal component analysis and heat map analysis

Principal component analysis was applied to the chemical composition, physical attributes, acrylamide and HMF contents (Figure 2) to further evaluate the differences and similarities between the samples. The results of PCA can be explained by two principal components (PC1 and PC2). PC1 explained 36.7% of the total variance, while PC2 explained 29.3%. The biplot shows that the samples collected from Nazilli, Kuşadası and Söke were different from other districts in terms of acrylamide content. The similarity between HMF, fat (%) and Lokma dessert draws attention to the amount of HMF in the fried Lokma dessert. L (inner) and L (outer) values were parallel. While a (inner) and moisture (%) showed a positive correlation, fat (%) and a (inner) showed a negative correlation. Variables such as L (inner), L (outer) and Width/Length ratio, HMF (mg/kg), Mn (mg/kg), fat (%) were in the same region, which shows that there was a relationship between them.

Cluster analysis was illustrated using a heat map to summarize similarities and differences among dessert samples in terms of chemical composition, acrylamide and 5-HMF (Figure 3). Overall, the heat map indicates distinct grouping patterns, with certain samples exhibiting comparatively high (red) or low (blue) intensities across specific variables. Notably, the Didim sample shows a pronounced deviation from the remaining samples across multiple mineral- and color-related parameters, consistent with its separation observed in the PCA, and this divergence is also supported by the clustering structure. In contrast, samples from Nazilli, Kuşadası, and Söke showed broadly comparable profiles, with predominantly moderate to low intensities across many variables, aligning with their proximity in the PCA space. Finally, Halka and the patisserie sample appear to be characterized by relatively higher intensities in processing- and color-associated indicators, together with increased acrylamide levels, distinguishing them from the other groups.

It was observed when the PCA and heat map results were evaluated together that significant chemical and physical differences were encountered between the examined samples. In the PCA biplot graph, the Didim sample was significantly distinguished from the other samples, especially in terms of mineral contents such as Ca, Cu, Zn, Fe and the a (outer) color parameter and such a case was confirmed by the high values of the relevant parameters in the heat map. Similarly, the Şambali sample stands out with its high moisture, K and ash content and had a different profile with low oil content and color values. The Nazilli, Kuşadası and Söke samples were located close to each other in both the PCA and heat map and generally represented a homogeneous group with more average values. When the hierarchical clustering between the variables is examined, it was seen that the color parameters (a and b values) were clustered in a correlated way with each other and the mineral contents also form a similar group. These findings revealed that the distinctive features between the products were shaped depending on both the compositional content and physical parameters and that the PCA and heat map analyses supported each other.

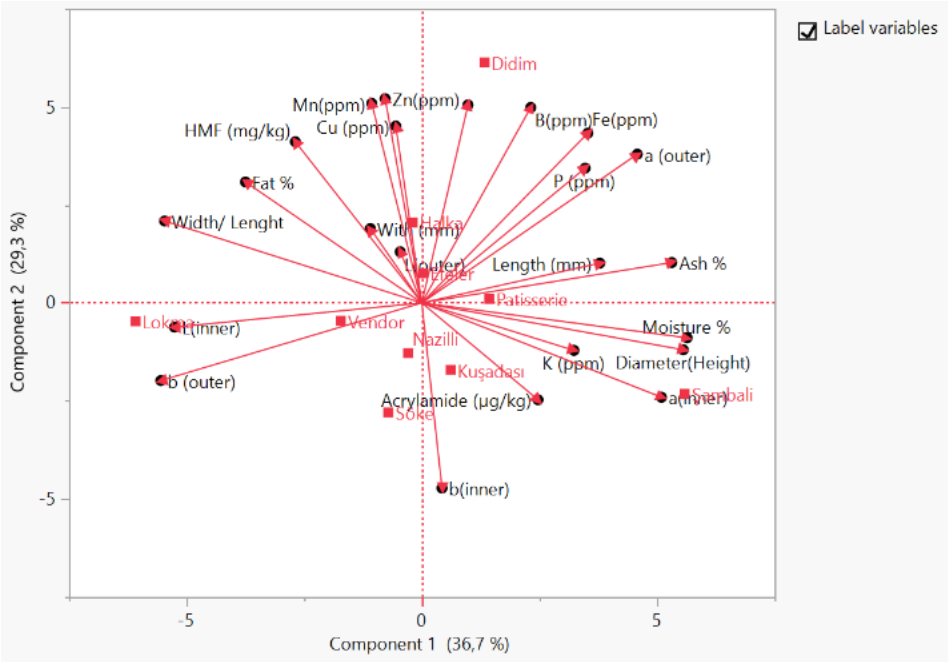

Figure 2. PCA biplot graph for compositions, Acrylamide (µg/kg) and HMF (mg/kg) contents of desserts.

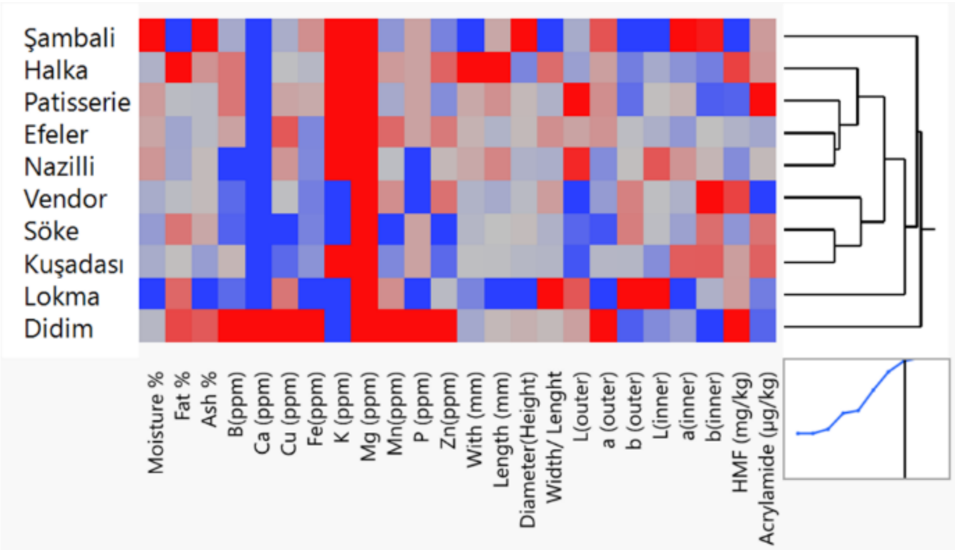

Figure 3. Heat map and clustering analysis of dessert samples. Blue colors indicate that results were less than the mean levels, while red colors indicate that results were higher than the mean levels.

Conclusions

Obtained results demonstrate that the physical and chemical characteristics of traditional desserts are not uniform across the supply chain. Physical attributes varied significantly according to both supply source and district, reflecting differences in shaping practices, standardization, and local processing conditions. Variability in product geometry (e.g., spherical Lokma, ring-shaped Halka, and rectangular Şambali) likely contributed to differences in color and size parameters. Similarly, compositional properties were influenced not only by dessert type but also by supply-chain and district-related factors, with the magnitude of variation depending on the specific chemical parameter evaluated. HMF and acrylamide concentrations were affected by both production practices (e.g., baking vs. frying, oil usage, and process control) and regional variability. Given that acrylamide formation is governed by the interaction of free asparagine and reducing sugars—whose levels differ between semolina- and wheat flour–based matrices—and is further promoted under high-temperature, low-moisture frying conditions, differences in formulation and processing are key determinants of contaminant levels.

Correlation analysis showed distinct association patterns for HMF and acrylamide. HMF was more closely related to baking-associated physical quality parameters, whereas acrylamide showed stronger relationships with chemical matrix characteristics, particularly trace element profiles. Additionally, using chemometric approaches, multivariate analyses consistently revealed that sample differentiation was driven by combined effects of compositional and physical variables. Both approaches identified distinct and similar sample groupings in a comparable manner, confirming the robustness of the observed patterns and highlighting the joint influence of formulation, processing, and regional factors on dessert quality and contaminant formation.

Present findings are expected to contribute to the accumulation of data for health risk assessments in Türkiye, European countries and globally, as well as support efforts to develop techniques to minimize chemical contaminants, acrylamide and HMF formation in traditional syrup-based desserts. These chemical contaminants could be reduced through strict compliance with the regulations and suitable manufacturing conditions in both manufacturers such as patisserie and vendors. Furthermore, non-legislative measures, e.g. “acrylamide toolbox” with available information how to mitigate in Turkish traditional dessert preparations could be effective on types of desserts. Further research is recommended to focus on effective mitigation strategies including optimizing production parameters to reduce the amount of these contaminants in desserts.

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