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Assessment of Maillard reaction products and oxidative stress markers in commercial noodle samples from Türkiye

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ABSTRACT

The Maillard reaction and oxidative degradation significantly impact the quality and safety of processed foods. This study systematically investigates for the first time the levels of Maillard reaction products—furosine, malondialdehyde (MDA), glyoxal (GO), and methylglyoxal (MGO)—in commercial noodle samples from Türkiye. A total of 13 noodle samples were analyzed to assess the impact of thermal processing on protein quality degradation and lipid oxidation. The results indicate that furosine levels ranged from 10.83 to 60.28 mg/100 g, with an average of 39.31 mg/100 g, suggesting varying degrees of heat treatment among the samples. MDA levels varied between 33.62 and 198.81 μg/100 g, with an average of 122.46 μg /100 g, indicating lipid oxidation influenced by processing conditions. GO and MGO levels ranged from 110.32 to 196.56 μg/100 g and 9.31–42.06 μg/100 g, respectively, aligning with previously reported levels in heat-processed foods. These findings highlight the need for optimizing processing conditions in noodle production to minimize the formation of undesirable Maillard reaction products and oxidative stress markers. Strategies such as controlled drying temperatures, vacuum drying, and the incorporation of antioxidant-rich ingredients may help reduce the accumulation of these compounds. Future research should explore the long-term dietary exposure to AGEs in noodles and assess their potential health implications.

1. Introduction

Noodle products have become one of the most essential components of the processed food industry due to their rapidly increasing consumption worldwide (Hou, 2020). The global instant noodle market was valued at USD 51.65 billion in 2021, rising to USD 54.6 billion in 2022 and USD 57.4 billion in 2023, with a projected compound annual growth rate (CAGR) of 5.65 % for 2023–2032. China leads global instant noodle consumption, followed by Indonesia, Japan, and Vietnam, while the Asia–Pacific region shows strong growth, particularly in demand for functional and healthier noodle varieties (Guner & Başdoğan, 2025). Globally, instant noodles are categorized into wheat-based, rice-based, and other starch-based types (e.g., corn starch noodles), with wheat-based products holding the largest consumption share. In Türkiye, instant noodle consumption has been steadily increasing, driven by urbanization, changing lifestyles, and the growing preference for convenient foods (Guner et al., 2024).

However, the high-temperature drying and cooking processes used in noodle manufacturing trigger chemical transformations such as the Maillard reaction, lipid oxidation, and related pathways, which can lead to nutrient loss and the formation of potentially harmful compounds, including acrylamide, hydroxymethylfurfural (HMF), furosine, and reactive carbonyl species such as glyoxal (GO) and methylglyoxal (MGO) (Anese et al., 1999). The Maillard reaction is a non-enzymatic browning process occurring between reducing sugars and amino acids during heat treatment (Martins & Van Boekel, 2005), contributing to desirable flavor and color but also resulting in the formation of advanced glycation end-products (AGEs) and other potentially toxic compounds, including acrylamide, HMF, furosine, GO, and MGO (Liu et al., 2025; Zhang et al., 2025). AGEs have been linked to oxidative stress,

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inflammation, and cardiometabolic disorders (Uribarri et al., 2010; Nie et al., 2020), with their formation influenced by factors such as temperature, water activity, and cooking time (Sharma et al., 2015; Rajan et al., 2018). In particular, high-temperature drying and frying in noodle processing can substantially increase the risk of AGE formation.

Several Maillard reaction markers are used to evaluate food quality and processing impact. Furosine is an early-stage Maillard product, formed by acid hydrolysis of Amadori compounds generated from lysine–reducing sugar interactions (Kathuria et al., 2023; Tu et al., 2020). It serves as a key indicator of thermal load and protein quality degradation, with higher levels indicating excessive heat treatment and reduced protein digestibility (Nath et al., 2022). Malondialdehyde (MDA) is a major secondary product of lipid peroxidation, widely used to assess oxidative deterioration in food matrices (Zhang et al., 2023; Wang et al., 2025a). Lipid oxidation in oil-containing products such as noodles is significantly influenced by both processing and storage conditions (Yang et al., 2021).

In advanced Maillard stages, GO and MGO emerge as highly reactive carbonyl compounds that act as precursors to AGEs, contributing to the modification of proteins via interaction with arginine and lysine residues (Hellwig & Henle, 2014; He et al., 2020; Hoseyni et al., 2024). Their accumulation is associated with oxidative stress, inflammation, cellular dysfunction, and accelerated aging processes (Jia et al., 2023). Dietary AGEs, including GO- and MGO-derived adducts, can be absorbed through the gastrointestinal tract and contribute to systemic AGE load, with potential roles in metabolic disorders (Zhu et al., 2024; Wang et al., 2025b). High-temperature processed foods, including instant noodles, can contain elevated GO and MGO levels, which have been reported to negatively impact protein functionality and nutritional quality (Rungratanawanich et al., 2021; Vlassara & Striker, 2011; Sergi et al., 2020; Birlouez-Aragon et al., 2010). Although this study does not directly assess health outcomes, controlling AGE precursors is recognized as an important quality parameter for processed cereal products.

In this study, four representative markers were selected to cover different stages of heat-induced quality changes in cereal-based foods: furosine (early-stage Maillard indicator of protein quality loss), MDA (lipid oxidation marker), and GO/MGO (reactive carbonyls and AGE precursors). Direct AGE quantification was not included due to the complexity of analytical methods required; instead, GO and MGO were used as practical indicators of AGE formation potential. The objective of this work is to determine furosine, MDA, GO, and MGO levels in commercial noodle products available in the Turkish market and to compare these parameters across different brands. The results will provide insight into Maillard-derived compound variation in noodle products, implications for nutritional quality, and guidance for manufacturers to optimize processing in order to minimize AGE formation.

2. Materials and methods

2.1. Materials

The noodle samples analyzed in this study were collected from retail markets in Istanbul, Turkey, to represent a variety of brands and seasoning types available in the national market. All samples were bag-type instant noodles processed using palm frying. Product specifications, including brand code, seasoning type, cooking type, and nutritional composition per 100 g, are summarized in Table 2.1(a) and Table 2.1(b).

Table 2.1 (a)
General product specifications of bag-type instant noodle samples collected from retail markets in Istanbul, Turkey.

For 100 g Product	Brand Code	Seasoning	Type	Cooking Type
Sample 1	Brand 1	Curry	Bag type Instant Noodle	Palm fried
Sample 2	Brand 1	Chicken	Bag type Instant Noodle	Palm fried
Sample 3	Brand 2	Chicken	Bag type Instant Noodle	Palm fried
Sample 4	Brand 3	Vegetable	Bag type Instant Noodle	Palm fried
Sample 5	Brand 4	Curry	Bag type Instant Noodle	Palm fried
Sample 6	Brand 3	Chicken	Bag type Instant Noodle	Palm fried
Sample 7	Brand 4	Special	Bag type Instant Noodle	Palm fried
Sample 8	Brand 3	Beef	Bag type Instant Noodle	Palm fried
Sample 9	Brand 2	Curry	Bag type Instant Noodle	Palm fried
Sample 10	Brand 5	Curry	Bag type Instant Noodle	Palm fried
Sample 11	Brand 3	Chicken	Bag type Instant Noodle	Palm fried
Sample 12	Brand 2	Tomato	Bag type Instant Noodle	Palm fried
Sample 13	Brand 2	Curry	Bag type Instant Noodle	Palm fried

2.2. Methods

2.2.1. Furosine analysis

Sample Hydrolysis: Approximately 1 g of sample was weighed into a Falcon tube, followed by the addition of 10 mL of 6 N HCl. The suspension was transferred into a 50 mL glass bottle, sealed tightly, and subjected to acid hydrolysis in a preheated oven at 110 °C for at least 24 h. Upon completion, the hydrolysate volume was adjusted to 20 mL with deionized water. From this solution, 0.5 mL was transferred to a Falcon tube, mixed with 2–3 mL of 10 % sodium acetate solution and the final volume was brought to 5.0 mL with deionized water. The mixture was passed through a cellulose acetate membrane filter and transferred into an HPLC vial for analysis (Li et al., 2021).

Furosine determination was conducted using a Shimadzu LC-20A HPLC system equipped with a UV detector. Chromatographic separation was achieved on an Agilent Zorbax SB-C8 column (4.6 × 250 mm, 5 μm). The mobile phase consisted of (A) 0.06 M sodium acetate buffer (pH 4.3, adjusted with acetic acid) and (B) acetonitrile. The gradient elution program was set as follows: 0–6 min, 100 % A; 6–10 min, 50 % A and 50 % B; 10–15 min, 100 % A

Quantification of furosine was achieved by external calibration using a certified furosine standard (Sigma-Aldrich, St. Louis, MO, USA). A series of standard solutions (0.5–10 μg/mL) were prepared in mobile phase A, and the calibration curve was constructed by plotting peak area against concentration. The linear regression showed a correlation coefficient (R^2) above 0.999. Sample concentrations were calculated from the calibration equation and expressed as mg furosine per 100 g of sample. The LOD was defined as the concentration with a signal-to-noise ratio (S/N) greater than three, and the LOQ as the concentration with S/N above ten. In our HPLC analysis, the LOD for Furosine was 1.8 μg/100 g, and the LOQ was 5.4 μg /100 g. All analyses were performed in triplicate. The flow rate was set at 1 mL/min, injection volume at 10 μL, detection wavelength at 280 nm, and the column temperature at 32 °C. The procedure followed the Sigma Aldrich Application Note 44, originally developed for the separation of furosine in dairy products, with adaptations for the noodle matrix.

2.2.2. GO and MGO analysis

Sample Preparation and Derivatization: A homogenized portion of each sample (5 g) was placed into a 50 mL polypropylene centrifuge tube, followed by the addition of 25 mL of methanol. The mixture was vortexed for 5 min to ensure complete extraction and then centrifuged at 8000 rpm for 5 min. From the resulting supernatant, 1 mL was transferred into a clean 10 mL glass tube, to which 1 mL of 0.1 M CH_3COONa buffer (pH 3) was added. For derivatization, 0.5 mL of 4-nitro-1,2-

Table 2.1 (b)
Nutritional composition of bag-type instant noodle samples per 100 g product.

For 100 g Product	Energy (kJ/kcal)	Total Fat (g)	Saturated Fat (g)	Carbohydrate (g)	Sugars (g)	Fiber (g)	Protein (g)	Salt (g)
Sample 1	380/91	3,9	0,5	11,6	0,1	0,8	2,0	1,4
Sample 2	398/95	4,1	1,1	12,3	0,1	0,3	2,1	1,4
Sample 3	426/102	3,8	1,3	15,0	0,5	1,0	1,2	1,3
Sample 4	385/92	4,0	0,8	11,7	0,1	0,9	2,0	1,0
Sample 5	427/103	2,5	1,1	13,0	0,1	0,7	1,7	0,6
Sample 6	405/97	4,6	0,6	11,5	0,1	0,9	2,0	1,0
Sample 7	310/83	2,6	1,2	13,2	0,2	0,8	1,7	0,5
Sample 8	340/81	2,9	0,9	12,1	1,2	0,6	1,8	0,7
Sample 9	380/91	3,9	0,5	11,6	1,1	0,8	2	0,9
Sample 10	405/97	4	1,8	12,3	1	0,5	2,4	0,9
Sample 11	398/95	4,1	1,1	12,3	0,1	0,3	2,1	0,9
Sample 12	344/82	3,1	0,9	11,7	1,5	0,6	2,0	0,6
Sample 13	340/81	3,0	0,8	11,9	1,1	0,5	1,9	0,6

Chemical reagents used for analytical procedures, including standards and solvents, were obtained from Sigma-Aldrich (St. Louis, MO, USA). All chemicals were of analytical or HPLC grade, depending on the analysis requirements.

phenylenediamine solution (prepared in 1 % methanol) was introduced, and the mixture was incubated at 70 °C for 20 min. After incubation, the solutions were filtered through 0.45 μm cellulose acetate membranes and stored until HPLC analysis (Cengiz et al., 2020).

Quantification of GO and MGO was carried out using a Shimadzu LC-20AT HPLC system equipped with an SPD-20A UV/VIS detector (Shimadzu Corporation, Kyoto, Japan). The chromatographic separation was performed on an Inersil ODS-3 column, maintained at 30 °C, using a mobile phase composed of methanol, water, and acetonitrile (42:56:2, v/v/v) at a flow rate of 1 mL/min. The detector was set at 254 nm for analyte monitoring (Cengiz et al., 2020).

2.2.3. Malondialdehyde (MDA) analysis

The determination of malondialdehyde (MDA) content in noodle samples was conducted by adapting a previously described procedure (Aksoy et al., 2022). For reagent preparation, 10 % trichloroacetic acid (TCA) was dissolved in deionized water, while 0.67 % thiobarbituric acid (TBA) was prepared in distilled water. The tetraethoxypropane (TEP) standard was prepared by diluting 0.5 mL of TEP to 100 mL with ethanol; from this solution, 0.1 mL was further diluted with TCA in 100 mL of deionized water. For sample extraction, 5 g (or 5 mL) of digested and undigested noodle samples were placed in 50 mL centrifuge tubes, and 25 mL of 10 % TCA was added to precipitate proteins. For undigested samples, 150 μL of 7.2 % butylated hydroxytoluene (BHT) was also incorporated. The mixtures were homogenized using an UltraTurrax® at 4293 g for 1 min, brought to a final volume of 50 mL with TCA, and centrifuged at 1073 g for 5 min. For derivatization, 1 mL of the resulting supernatant was combined with 1 mL of TBA solution and incubated in a water bath at 90 °C for 30 min, followed by cooling to room temperature. An aliquot (2 mL) of the reaction mixture was transferred to amber HPLC vials, filtered through a 0.45 μm membrane, and subjected to chromatographic analysis. For calibration, 0.1 mL of the TEP standard solution was mixed with 1 mL of TBA solution, incubated at 90 °C for 10 min, cooled, filtered through a 0.45 μm membrane, and transferred into 2 mL vials for injection into the HPLC system.

The chromatographic separation was performed on a Shimadzu LC-20AT system equipped with an SPD-20A UV/VIS detector (Shimadzu Corporation, Kyoto, Japan). The mobile phase consisted of a 0.05 M KH_2PO_4 buffer/methanol/acetonitrile mixture (72:17:11, v/v/v). Detection and quantification of MDA were carried out at emission wavelengths of 515 nm and 550 nm, respectively. An Inertsil ODS-3 column (5 μm, 4.6 mm × 150 mm) was used, with a flow rate of 1 mL/min, injection volume of 10 μL, and column temperature maintained at 30 °C.

2.2.4. Statistical analysis

The data obtained from the analyses were investigated using the JMP 13.0.0 (SAS Institute Inc. Cary, NC, USA). One-way analysis of variance (ANOVA) explored the statistical differences and the differences between the groups were determined by using the Tukey's honestly significant difference (HSD) test. Correlation analyses were also performed using Pearson's correlation coefficient to evaluate the relationships between nutritional components and the levels of furosine, MDA, GO, and MGO. All results are presented as mean ± standard deviation (SD), and differences were considered statistically significant at $p < 0.05$.

3. Results and discussion

In this study, the levels of compounds associated with the Maillard reaction and oxidative stress—namely furosine, malondialdehyde (MDA), glyoxal (GO), and methylglyoxal (MGO)—were determined in commercially available noodle samples from the Turkish market, and comparisons were made among different brands. The quantitative findings are presented in Table 3.1. Across the samples, significant differences ($p < 0.05$) were observed in the levels of furosine, MDA, GO, and MGO. Furosine levels ranged from 10.83 to 60.28 mg/100 g, MDA from 33.62 to 198.81 μg/100 g, GO from 110.32 to 196.56 μg/100 g, and MGO from 9.31 to 42.06 μg/100 g. The results indicate that sample 5 exhibited the highest levels of MDA and MGO, sample 3 showed the highest GO content, and sample 4 showed the highest furosine content. The correlation between the nutritional values of the noodle samples and the levels of furosine, MDA, GO, and MGO was investigated and findings are presented in Table 3.2. The results showed that only GO levels were significantly positively correlated with the carbohydrate content of the samples ($r = 0.71$, $p = 0.006$), whereas furosine, MDA,

Table 3.1
Concentrations of Furosine, MDA, GO and MGO in Noodle Samples[a].

	Furosine	MDA	GO	MGO
1	10.83 ± 0.31^{m}	105.21 ± 3.51^{i}	137.45 ± 4.36^{ef}	29.12 ± 1.53^{c}
2	48.54 ± 2.71^{c}	185.14 ± 5.13^{b}	166.21 ± 3.79^{c}	13.55 ± 1.00^{j}
3	46.83 ± 1.61^{d}	170.56 ± 6.66^{c}	196.56 ± 3.61^{a}	31.02 ± 2.08^{b}
4	60.28 ± 2.08^{a}	33.62 ± 2.08^{m}	110.32 ± 3.21^{j}	9.31 ± 0.58^{m}
5	56.59 ± 2.19^{b}	198.81 ± 6.43^{a}	164.51 ± 4.04^{c}	42.06 ± 2.08^{a}
6	38.11 ± 2.58^{h}	90.13 ± 2.35^{j}	130.78 ± 2.52^{g}	15.42 ± 1.15^{i}
7	38.9 ± 1.93^{g}	147.25 ± 6.00^{e}	154.88 ± 3.21^{d}	19.75 ± 1.01^{g}
8	20.66 ± 2.36^{l}	83.45 ± 3.00^{k}	127.14 ± 3.21^{h}	9.51 ± 0.58^{l}
9	34.53 ± 2.11^{j}	123.69 ± 4.20^{g}	170.15 ± 3.61^{b}	23.14 ± 1.53^{e}
10	32.01 ± 2.85^{k}	109.47 ± 3.51^{h}	169.05 ± 6.01^{b}	23.56 ± 1.53^{d}
11	44.36 ± 3.33^{e}	69.63 ± 1.53^{l}	134.21 ± 3.06^{f}	10.13 ± 0.58^{k}
12	35.22 ± 1.92^{i}	130.34 ± 3.61^{f}	121.63 ± 3.21^{i}	18.23 ± 1.00^{h}
13	44.12 ± 2.84^{f}	150.17 ± 3.22^{d}	138.17 ± 5.13^{e}	20.38 ± 1.53^{f}

[a]Furosine values are expressed as mg/100 g and MDA, GO, MGO values are expressed as μg/100 g. The results were presented as mean ± standard deviation. All reported statistical differences are based on ANOVA followed by Tukey's test at $p < 0.05$. Superscript letters indicate significant differences within rows.

Table 3.2
Pearson Correlations Between Furosine, MDA, GO, MGO and Nutritional Composition of Noodle Samples (n = 13).

	Significance	Energy (kJ)	Total Fat (g)	Saturated Fat (g)	Carbohydrate (g)	Sugars (g)	Fiber (g)	Protein (g)
Furosine	r	0.35	−0.03	0.24	0.31	−0.34	0.00	−0.20
	p	0.24	0.92	0.44	0.31	0.25	0.99	0.50
MDA	r	0.14	−0.43	0.26	0.52	0.01	−0.10	−0.42
	p	0.65	0.14	0.38	0.07	0.96	0.75	0.15
GO	r	0.44	0.0005	0.48	0.71	−0.04	0.09	−0.39
	p	0.13	1.00	0.1	0.006*	0.88	0.77	0.19
MGO	r	0.4	−0.33	0.14	0.45	−0.08	0.33	−0.40
	p	0.18	0.26	0.65	0.13	0.78	0.27	0.17

Values represent Pearson's correlation coefficients (r) with corresponding significance levels (p). *p < 0.05 marked with *.

and MGO levels were not significantly associated with the nutritional values. Although MDA and MGO exhibited moderate correlations with carbohydrates (r = 0.52, p = 0.07; r = 0.45, p = 0.13, respectively), these correlations were not statistically significant. Overall, the results suggest that nutritional composition does not markedly affect the accumulation of these compounds. These results reveal the influence of processing conditions on the accumulation of these compounds and demonstrate the extent to which their presence is related to specific production parameters. This indicates substantial variability among brands. These differences are likely attributable to variations in thermal processing conditions—such as steaming duration, frying temperature and time—as well as differences in drying techniques and the type of frying oil used. In addition, moisture content prior to frying and storage conditions may also have contributed to the observed variability. Building on these observations, the findings are further enriched through comparisons with similar cereal-based bakery products reported in the literature, leading to practical recommendations regarding critical control points in noodle manufacturing.

3.1. Evaluation of furosine levels

In the present study, furosine levels in the analyzed noodle samples ranged from 10.83 to 60.28 mg/100 g, with an average value of 39.31 mg/100 g. Sample 4 exhibited the highest furosine content (60.28 mg/100 g; $p < 0.05$), whereas Sample 1 had the lowest (10.83 mg/100 g; $p < 0.05$), indicating statistically significant variation among brands. Furosine is a well-established marker of the early stages of the Maillard reaction, formed through the acid hydrolysis of Amadori compounds resulting from the interaction between lysine and reducing sugars. Consequently, the concentration of furosine serves as a valuable indicator of both thermal processing intensity and the extent of protein quality degradation (Delgado-Andrade & Fogliano, 2018; Resmini & Pellegrino, 1991). Although the values obtained fell within a moderate range compared to other cereal-based products, the wide variability among samples suggests that different processing conditions were applied. From a technological perspective, such a balance may be advantageous for maintaining both safety and sensory attributes while limiting excessive nutritional losses.

Given that both noodles and pasta are wheat-based products, direct comparison is appropriate. Literature reports indicate furosine levels ranging from 13 to 60 mg/100 g in gluten-free pasta samples (Giannetti et al., 2013), closely overlapping with the range found in the present study. In conventional pasta, drying temperature markedly influences furosine formation, with high-temperature drying resulting in concentrations as high as 390–562 mg/100 g protein (approximately 50–70 mg/100 g product) (Hidalgo & Brandolini, 2011). Products dried under milder conditions generally exhibit lower furosine levels, underscoring the sensitivity of furosine formation to processing parameters. This trend is partially mirrored in our findings, although our regression analysis revealed no significant correlations between furosine levels and the nutritional composition of the samples ($p > 0.05$). Such observations suggest that noodle manufacturing processes could be fine-tuned to further minimize furosine without compromising product stability.

Rice-based products, particularly rice noodles and cooked rice, typically exhibit lower furosine levels due to their inherently low reducing sugar content and reduced lysine concentration. Several studies have reported furosine concentrations in the range of 5–20 mg/100 g product for rice noodles (Giannetti et al., 2013; Lamberts et al., 2008), which are lower than those detected in wheat-based noodles. This difference is not only a function of raw material composition but also the prevalent use of moist-heat treatments, such as boiling, which favor minimal Maillard development. The contrast emphasizes that product matrix and amino acid profile are as influential as thermal conditions in determining furosine formation. Consequently, wheat-based noodles inherently have a higher potential for furosine generation, even when processed under similar temperature–time combinations.

Low-sugar extruded cereal products also provide a meaningful comparison. Gluten-free breakfast cereals have been reported to contain furosine levels of approximately 15–25 mg/100 g product (Feng et al., 2022a), which are below the average values found in the present noodle samples. However, in extruded products, parameters such as feed moisture, screw speed, and die temperature play a decisive role in furosine accumulation. The higher values in our noodle samples may partly reflect the continuous heat exposure during frying or hot-air drying, as opposed to the shorter, high-intensity heating in extrusion, which limits time-dependent Maillard development. This suggests that cumulative heat load, rather than peak temperature alone, is a critical driver of furosine concentration across different low-sugar, protein-containing food systems.

Overall, the furosine concentrations in the noodles analyzed here were higher than those in other low-sugar, hot-processed products such as rice noodles and extruded cereals, yet substantially lower than those typically reported for high-sugar products like biscuits and cakes. These findings reinforce the pivotal role of product formulation—particularly sugar type and protein source—and processing conditions in modulating Maillard reaction progression. It should be noted that the furosine levels reported here reflect uncooked noodle samples. Cooking or rehydration with hot water, as typically performed before consumption, is likely to influence these values. Previous studies on pasta and cereal-based products have shown that moist-heat treatments such as boiling can cause partial loss of furosine, primarily due to leaching of water-soluble Maillard products into the cooking medium. Therefore, the actual furosine intake from prepared noodles may be lower than the values reported in this study, although the extent of reduction would depend on cooking time, temperature, and water-to-product ratio. From a product development perspective, this insight supports targeted formulation and process control strategies aimed at minimizing furosine levels without compromising desired texture and flavor profiles.

3.2. Evaluation of malondialdehyde (MDA) levels

Malondialdehyde (MDA) is a major secondary product of lipid peroxidation and is widely recognized as an indicator of oxidative deterioration in food systems. Its accumulation is influenced by processing temperature, storage conditions, and particularly the lipid content and

degree of unsaturation of the product. In the noodle samples analyzed in this study, MDA concentrations ranged from 33.62 to 198.81 μg per 100 g (mean ~122 μg/100 g), corresponding to approximately 0.34–1.99 mg/kg, with an average value of ~1.22 mg/kg. Sample 5 exhibited the highest MDA content (198.81 μg/100 g; $p < 0.05$), while Sample 4 had the lowest (33.62 μg/100 g; $p < 0.05$), demonstrating significant variability among brands. These levels are consistent with those reported in certain low-sugar, hot-processed cereal-based products and indicate that measurable lipid oxidation occurred during processing and/or storage.

Low-sugar staple foods such as boiled pasta, rice, yeast-leavened bread, and rice noodles generally exhibit much lower MDA accumulation due to their very low lipid contents. Plain cooked pasta or rice (typically <2 % fat) stored under controlled conditions shows TBARS values well below 1 mg/kg, while freshly prepared products often remain close to the detection limit (Feng et al., 2022b; Okolie & Okugbo, 2013). Similarly, steamed or boiled rice noodles have extremely low MDA formation. Yeast-leavened bread stored under appropriate conditions typically maintains values around ~0.5–0.8 mg/kg. In contrast, noodles formulated with higher fat contents and/or processed by frying exhibit markedly higher oxidation levels. In particular, the frying process, which is common in instant noodles, promotes lipid oxidation compared to high-moisture cooking methods.

The mean MDA value observed in the noodle samples (~1.22 mg/kg) is comparable to that of moderately fatty, low-sugar cereal-based snacks. Biscuits and cookies, for instance, have been reported to contain 0.8–1.3 mg/kg MDA when fresh (Rababah et al., 2012; Gebreselassie & Hall, 2016). However, these products generally have relatively high sugar contents, which limits their relevance as direct comparators for low-sugar products. In contrast, low-sugar, high-fat fried snacks such as potato chips typically exhibit MDA levels of about 1.3 ± 0.5 mg/kg (Feng et al., 2022a; Ma et al., 2021). The highest level detected in our study (~1.98 mg/kg) overlaps with values reported for intensely fried products containing higher proportions of unsaturated fats, suggesting that certain noodle formulations and processing conditions may be more prone to oxidation. However, our correlation analysis did not reveal a significant association between MDA levels and fat content in the samples ($p > 0.05$), indicating that factors other than nutritional composition—such as frying temperature, oil turnover, or antioxidant presence—likely contributed to the observed variability.

Previous studies have shown that protein- or fat-enriched snacks may present higher MDA levels. For example, protein-enriched noodles have been found to contain higher TBARS values compared to control samples, attributed to increased unsaturated fatty acid content and the prooxidant effect of heme iron in meat (Aksoy et al., 2022; Papastergiadis et al., 2014a). Similarly, salted and dried meat products have exhibited marked increases in MDA during storage, likely due to the oxidative effects of sodium chloride (Díaz et al., 2014). In this context, the noodle sample with the highest MDA content in our study likely originated from a formulation with high unsaturated fat content and insufficient antioxidant protection.

From a sensory perspective, most noodle samples remained within acceptable oxidation limits. Bitterness in snack products generally becomes perceptible to consumers when MDA levels exceed approximately 1–2 mg/kg (Hülsebusch et al., 2025; Campo et al., 2006), and only the highest values in our study approached this threshold. The mean value (~1.22 mg/kg) reflects mild oxidation, although some products may be at risk of compromising flavor stability. Improper storage conditions, such as oxygen exposure and elevated temperatures, could further accelerate MDA accumulation after purchase, potentially pushing products beyond the sensory acceptability threshold.

From a health perspective, MDA can react with DNA to form mutagenic and potentially carcinogenic adducts (e.g., M1dG) (Cordiano et al., 2023; Marnett, 1999). The European Food Safety Authority (EFSA) has proposed a tolerable daily intake (TDI) of approximately 30 μg/kg body weight (≈1.8–2.1 mg/day for adults). In our study, a 100 g portion of noodles contained ~122 μg MDA, corresponding to only about 6–7 % of the TDI (Efsa Panel On Biological Hazards Biohaz, 2011). While this indicates a low acute risk, regular consumption could contribute to cumulative oxidative stress and inflammation.

Minimizing MDA accumulation in processed foods is essential for both nutritional quality and consumer safety. Effective strategies include the use of natural or synthetic antioxidants (Yang et al., 2020; Papastergiadis et al., 2014b), supplementation with polyphenol-rich extracts (e.g., rosemary, green tea) or tocopherols (Rababah et al., 2012), the selection of oils with higher oxidative stability, optimization of frying parameters (e.g., lower temperatures, vacuum frying), and the application of advanced packaging solutions with oxygen barrier or scavenging properties. The MDA levels presented in this study correspond to uncooked noodle samples. During preparation, rehydration or cooking in hot water can alter these values through both dilution effects and oxidative changes. Moist-heat treatments typically result in partial leaching of lipid oxidation products into the cooking water, which may lower the measurable MDA content in the final serving. Conversely, certain high-fat formulations may experience additional oxidation if exposed to excessive heating during preparation. Consequently, the consumer's actual MDA exposure may differ from the analytical values reported here, highlighting the importance of assessing both raw and prepared forms in future studies. Overall, although average MDA levels were in line with similar cereal-based snacks, the absence of significant correlations with nutritional composition ($p > 0.05$) suggests that processing and storage conditions are the primary determinants of oxidative stability in noodle products (Tsai et al., 2025; Paravisini & Peterson, 2019; Papastergiadis et al., 2014b).

3.3. Evaluation of glyoxal (GO) and methylglyoxal (MGO) levels

The levels of glyoxal (GO) and methylglyoxal (MGO) detected in the commercial noodle samples analyzed in this study reflect the accumulation of reactive carbonyl species (RCS) generated during thermal processing. GO concentrations ranged from 110.32 to 196.56 μg/100 g (mean 147.38 μg/100 g), while MGO levels varied between 9.31 and 42.06 μg/100 g (mean 20.08 μg/100 g). These results indicate that frying and drying steps used in noodle manufacturing triggered some Maillard reaction, although MGO—the more reactive α-dicarbonyl—remained at relatively low concentrations, likely due to the absence of high-fructose or other ketose-type sugars in the formulation.

When compared to other low-sugar content, hot-processed cereal-based products, the GO/MGO values in noodles are within a moderate range. For example, studies on plain boiled pasta and rice noodles—both typically containing < 2 % fat and minimal free sugars—show negligible α-dicarbonyl accumulation under high-moisture, low-temperature cooking conditions [311]. Even when subjected to mild drying, such products maintain GO and MGO at trace levels, far below the values observed in fried noodles. In our samples, GO ranged from 110.32 μg/100 g (Sample 4) to 196.56 μg/100 g (Sample 3), while MGO varied from 9.31 μg/100 g (Sample 4) to 42.06 μg/100 g (Sample 5), with significant differences among brands ($p < 0.05$). The slightly higher GO in our samples (~147 μg/100 g) compared to boiled pasta or rice noodles is attributable to the frying step, which briefly exposes the product to higher temperatures and reduced moisture, favoring limited Maillard fragmentation.

Among other low-sugar dry products, unsweetened crackers or crispbread can exhibit considerably higher α-dicarbonyl levels than noodles, often due to their very low final moisture content, added salts, and extended baking times. For instance, GO in such products can reach 456–1125 μg/100 g and MGO 727–1013 μg/100 g (Cengiz et al., 2020), which is 5–10 times higher than noodle levels. These differences highlight the role of product formulation (absence of added sugars in noodles) and process severity (short frying vs. long dry baking) in limiting α-dicarbonyl formation.

Low-sugar breakfast cereals that are toasted or extruded also tend to

accumulate more GO/MGO than noodles, even without added sugar coatings. In puffed or toasted cereals, high-temperature dry heat promotes Maillard-derived dicarbonyls, sometimes exceeding 200–300 μg/100 g GO and 100–200 μg/100 g MGO (Çintesun et al., 2022). In contrast, our noodles—despite being fried—show lower values, likely due to a combination of moisture retention during frying and limited sugar precursors. It should be noted, however, that our correlation analysis did not reveal a significant association between MGO levels and sugar content ($p > 0.05$). In contrast, GO levels showed a significant positive correlation with carbohydrate content ($r = 0.71$, $p = 0.006$), suggesting that carbohydrate composition may play a role in GO accumulation in noodles.

By comparison, high-sugar products such as biscuits, cookies, and cakes often contain GO and MGO levels an order of magnitude greater than noodles (Cengiz et al., 2020; Fallico et al., 2022; Çintesun et al., 2022), largely due to the abundance of reducing sugars and prolonged dry heat exposure. While these comparisons illustrate the upper extremes of α-dicarbonyl formation, they are of limited nutritional relevance to low-sugar noodle formulations and are therefore included here only as a reference point.

Overall, the measured GO (~147 μg/100 g) and MGO (~20 μg/100 g) levels in noodles are moderate for hot-processed cereal-based products, and considerably lower than in most dry-baked goods. Their low sugar content, simple formulation, and moderate heat load during frying limit the generation of these potentially harmful carbonyls. Taken together, these findings suggest that while MGO remained relatively low and unrelated to nutritional composition, GO accumulation was significantly associated with carbohydrate content, highlighting the importance of formulation and processing control in mitigating reactive carbonyl formation.

4. Conclusion

This study provides a detailed assessment of the levels of key Maillard reaction products (furosine, GO, MGO) and a lipid oxidation marker (MDA) in commercial noodle products available in the Turkish market. These compounds act as indicators of thermal stress, protein degradation, lipid peroxidation and the formation of advanced glycation end products (AGEs), all of which are critically influenced by formulation and processing parameters.

The results revealed significant differences among the samples: sample 5 contained the highest MDA and MGO levels, sample 3 the highest GO content, and sample 4 the highest furosine content. Moreover, only GO levels showed a significant positive correlation with carbohydrate content, whereas furosine, MDA, and MGO levels were not significantly associated with nutritional values. Overall, these findings point to clear variability among brands, suggesting that differences in processing parameters rather than nutritional composition play the dominant role in determining compound accumulation.

Building on these findings, a refined interpretation of the chemical markers elucidates the critical role of processing conditions in modulating their formation and offers valuable insights into the mechanistic determinants of the observed inter-sample variability. The detection of moderate furosine levels suggests that early Maillard reactions are active in noodle production, although the absence of added reducing sugars helps to limit their accumulation. Similarly, MDA levels indicate the presence of mild to moderate oxidative stress, especially in samples with higher fat content or exposure to prolonged frying. The GO and MGO concentrations provide further insights into carbonyl stress, revealing that while GO accumulation may occur at moderate levels, MGO formation is generally well-controlled due to the low sugar and neutral pH characteristics of noodle formulations. The findings clearly demonstrate that these chemical indicators are significantly influenced by the thermal processing conditions applied during manufacturing.

From an industrial perspective, these results underline the necessity of carefully optimizing production parameters such as frying temperature, drying duration, and antioxidant use to reduce the formation of undesirable compounds. Regular monitoring of these markers can contribute to improved nutritional quality, extended shelf life, and enhanced consumer safety in noodle products.

Furthermore, this study provides a valuable benchmark for future reformulation efforts and quality assurance programs in the cereal-based food industry. Continued research into clean-label antioxidant strategies, alternative processing technologies, and glycation-reducing interventions will be essential for developing next-generation noodle products that meet both health and sensory expectations.

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CRediT authorship contribution statement

BAŞDOĞAN Hakan: Funding acquisition, Resources, Project administration, Writing – review & editing. **PEHLIVANOGLU Halime:** Writing – review & editing, Conceptualization. **PALABIYIK Ibrahim:** Writing – review & editing, Validation, Supervision. **GUNER Cihat:** Writing – review & editing, Writing – original draft. **ÖZTÜRK Nurşah Zeynep:** Writing – review & editing, Writing – original draft. **BOSTANCI Ferhat:** Writing – review & editing, Formal analysis. **YAMAN Mustafa:** Writing – review & editing, Methodology.

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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