Formation of advanced glycation end products precursors in apricots: a comprehensive market-based study

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Summary
Advanced glycation end products (AGEs) are a group of complex products formed by non-enzymatic glycation of biological macromolecules and are considered undesirable compounds, with glyoxal (GO) and methylglyoxal (MGO) acting as their precursors. This study investigated the relationship between AGE precursors and sugar composition in sun-dried and sulfured-dried apricots obtained from marketplaces in various regions throughout Istanbul (Turkey). A total of 54 samples (27 sun-dried, 27 sulfured-dried) were analysed using high-performance liquid chromatography to determine GO, MGO, glucose, fructose, and saccharose contents. The levels of GO and MGO in sun-dried apricots ranged from 0.040 mg·kg^{-1} to 1.595 mg·kg^{-1} and from 0.488 mg·kg^{-1} to 23.701 mg·kg^{-1}, respectively. GO and MGO content of sulfured-dried apricots ranged from 0.030 mg·kg^{-1} to 1.176 mg·kg^{-1} and 14.950 mg·kg^{-1} to 141.327 mg·kg^{-1}, respectively. On average, MGO content in sulfured-dried apricots was approximately five times higher than in sun-dried samples, indicating a notable difference. Variations in sugar content, processing temperature, storage time, sulfur content, and antioxidant activity may influence GO and MGO formation in dried apricots.

Keywords
glyoxal; methylglyoxal; sun drying; sulfur drying; apricot

Heterogeneous advanced glycation end product (AGE) compounds are formed due to the non-enzymatic reaction of reducing sugars such as glucose and fructose with proteins or lipids [1]. These compounds are produced endogenously in the body. Also, they can be taken into the body exogenously through air pollutants and cigarette smoke, as well as cooking and processing foods containing high sugar, protein, and fat at high temperatures [2].

There are three different pathways of AGE formation: Maillard reactions, polyol pathway, and lipid peroxidation [3]. The Maillard reaction results in the formation of glycated reversible molecules, primarily the unstable Shiff base and then the stable Amadori products. Further exposure of Amadori products results in the formation of dicarbonyl groups, which are AGE precursors, such as glyoxal (GO), methylglyoxal (MGO), and 3-deoxyglucosone. These groups also react with lysine or arginine to form irreversible AGEs [2, 3]. Methylglyoxal-hydroimidasalone (MG-H1), carboxymethyl-lysine (CML), carboxyethyl-lysine (CEL), pentosidine, and pyrraline are considered the significant AGEs from endogenous or exogenous sources. Due to the heterogeneous nature of AGEs, it is often difficult to precisely measure their formation. However, CML, CEL, and pentosidine are widely used as biomarkers to measure glycation [4]. Another reason for the formation of AGEs is the incubation of proteins with lipid peroxidation products. Glucose can also be converted to fructose, which can form very potent glycation agents via the polyol, and this pathway also promotes glycation [3]. Parameters such as cooking time, temperature, reactant concentration, presence of water, and pH are significantly effective in forming AGEs through these pathways [4].

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Although many studies suggest that dietary AGEs and their precursors may contribute to oxidative stress and inflammation, some researchers argue that their impact is relatively minor compared to endogenously formed AGEs. High levels of AGEs have been associated with Type 2 diabetes mellitus, as well as carotid thickening, ischemic heart disease, uremic cardiomyopathy, and renal failure in diabetic patients. The risk-increasing effects of AGEs in the formation of many diseases, such as Alzheimer's disease, acute kidney failure, atherosclerosis, hypertension, various types of cancer, allergies, and polycystic ovary syndrome, have also been reported [3].

New technologies such as heat, dehydration, ionisation, and irradiation used in the series production of foods have increased the formation and amount of AGEs in modern foods [5]. Increased consumption of these foods contributes to the body's total AGE load in addition to that generated endogenously [6]. Today, it is thought that people consume about 100–300 μmol per day or 16 000 kU per day AGE through diet, and this amount is high [2, 7]. Therefore, inhibiting AGE formation during food processing and reducing the AGE content of the diet are seen as two critical approaches to limiting these harmful components [8].

It is stated that fruits provide a protective effect against many chronic diseases due to the dietary fibre, various vitamins, minerals, polyphenols, and antioxidant activity components. Consumption of dried fruit is also thought to contribute to more fruit intake in the diet and thus to a better diet quality [9]. International Nut and Dried Fruit Council stated in its 2020–2021 report [10] that the production of selected dried fruits is approximately 2.9 million tons, and dried apricots constitute approximately 6 % of the world's dried fruit production. However, the Maillard reaction, which produces AGEs, can occur during heat treatment in many snacks containing significant amounts of protein and carbohydrates. Typical examples are processed foods such as canned soups and nuts, and dried fruits [8]. Therefore, it is essential to determine the levels of AGE precursors GO and MGO in dried apricots, which are dried fruits with a high production and consumption rate, and to examine the relationship of these components with the sugar content of apricots.

Besides having undergone sun-drying or sulfurisation processes, the dried apricots examined in this study naturally contain reducing sugars such as glucose and fructose and non-reducing saccharose. In addition to the limited data on the content of AGE precursors in dried fruits in the literature, few studies are comparing sun-dried and sulfured-dried apricots [11, 12]. Therefore, this study aimed to explore the sugar components, GO and MGO contents of dried apricots, which are a type of dried fruit recommended for consumption in the nutrition guides of many countries, and to evaluate the effects of sugar components and sun-drying and sulfuring techniques on the formation of AGEs in dried apricots.

MATERIALS AND METHODS

Chemicals

Glucose, fructose, saccharose, glyoxal (GO), methylglyoxal (MGO), methanol, acetonitrile, 4-nitro-1,2-phenylenediamine, and sodium acetate were supplied from Sigma-Aldrich (St. Louis, Missouri, USA).

Samples

A total of 54 samples were studied, including 27 unsulfured sun-dried apricots and 27 sulfured machine heat-dried apricots. Samples were randomly obtained from various retail markets in different districts of Istanbul (Turkey), to reflect regional diversity and consumer-accessible variability. All samples were transported to the laboratory under ambient conditions and stored at 4 °C in a refrigerator until analysis for a maximum 7 days. Due to market-based sample collection, detailed information regarding the geographic origin, cultivar, and maturity level of the apricots was not available.

Extraction and derivatisation of glyoxal and methylglyoxal

The GO and MGO extraction method in foodstuffs presented by Cengiz et al. [13] was used with minor modifications. First, each dried apricot sample was homogenised using a blender. Then, 5 g of each dried apricot sample was weighed into a 50 ml plastic tube and 25 ml of methanol was added. The sample was extracted for 2 min using an Ultra-Turrax homogeniser (IKA, Staufen, Germany) and centrifuged at 8 000 ×g for 5 min. Then, 0.5 ml of the liquid sample was transferred to a 10 ml glass tube and 2 ml of sodium acetate buffer (0.1 mol·l^{-1}, pH 3) was added. Afterwards, the derivatisation solution was prepared by 4-nitro-1,2-phenylenediamine in 1% methanol, and 0.5 ml of this solution was added. The incubation of the mixture was accomplished for 20 min at 70 °C. Then, the samples were filtered employing a pore size 0.45 μm cellulose acetate filter (Sartorius, Göttingen, Germany).

Extraction of sugar components

Sugar extraction of the apricots was performed using the CENGIZ et al. [13] procedure with some modifications. First, 5 g of the homogenised dried apricot sample was weighed into a 50 ml plastic falcon tube. Then, 50 ml of distilled water was added and the sample was extracted for 5 min using an Ultra-Turrax homogeniser. The final volume was then made up to 50 ml with distilled water. This mixture was centrifuged at 8 000 ×*g* for 5 min. Finally, the samples were filtered through a 0.45 μm cellulose acetate filter and injected into the high-performance liquid chromatograph (HPLC).

High-performance liquid chromatography

GO and MGO amounts were determined by HPLC employing the procedure presented by CENGIZ et al. [13] with minor modifications. A LC 20AT pump (Shimadzu, Kyoto, Japan) with a Shimadzu SPD-20A UV/Vis detector was used in this study. A mobile phase of methanol-water-acetonitrile (4 : 56 : 2, v/v/v) was used for the analysis. The wavelength was set to 255 nm. Inertsil ODS-3 column (250 mm in length, 4.6 mm in diameter, 5 μm particle size; GL Sciences, Tokyo, Japan) was employed to separate GO and MGO, and the flow rate was 1 ml·min^{-1}. Instead of the Zorbax 300 SB-C-18 column (Agilent Technologies, Santa Clara, California, USA) employed in the reference methodology, we employed an Inertsil ODS-3 HPLC column, which permitted more satisfactory separation in our investigation. The oven temperature of the column was 30 °C.

Detection of sugar components

In our study, HPLC conditions explained by CENGIZ et al. [13] were applied to measure sugar content. An HPLC system consisting of an LC 20AT pump with a RI-20A refractive detector (Shimadzu), mobile phase acetonitrile-water (80 : 20, v/v) was used. An NH2 column, 250 mm × 4.6 mm, 5 μm particle size (Agilent Technologies) was used to separate fructose, glucose, and saccharose at a flow rate of 2 ml·min^{-1}. The column oven temperature was 30 °C.

Quality control

To ensure accuracy and reliability, all chemical analyses were performed in triplicate (n = 3) for each sample. Results are reported as mean values.

RESULTS AND DISCUSSION

HPLC chromatograms of GO and MGO standards and sulfured-dried apricots (sample No. 10) are presented in Fig. 1 and Fig. 2. The chromatograms show that GO and MGO were well separated with the HPLC technique. The types of the samples and the determined contents of GO, MGO, glucose, fructose, and saccharose in sun-dried and sulfured-dried apricots are given in Tab. 1 and Tab. 2. The detected contents of GO and MGO in sun-dried and sulfured-dried apricots ranged from 0.030 mg·kg^{-1} to 1.595 mg·kg^{-1} and from 0.488 mg·kg^{-1} to 141.327 mg·kg^{-1}, respectively (total GO and MGO ranged from 0.947 mg·kg^{-1} to 142.204 mg·kg^{-1}). GO and MGO contents were determined in all 54 dried apricot samples examined. When the GO and MGO contents of dried apricots were compared, it was observed that MGO was higher in both sun-dried apricot and sulfured-dried apricot samples. The highest GO contents were found in sun-dried apricots with 1.475 mg·kg^{-1} and 1.595 mg·kg^{-1}, while the lowest value was found in sulfured-dried apricots with 0.030 mg·kg^{-1}. However, the highest MGO contents were significantly found in sulfured-dried apricots with 129.427–141.327 mg·kg^{-1}.

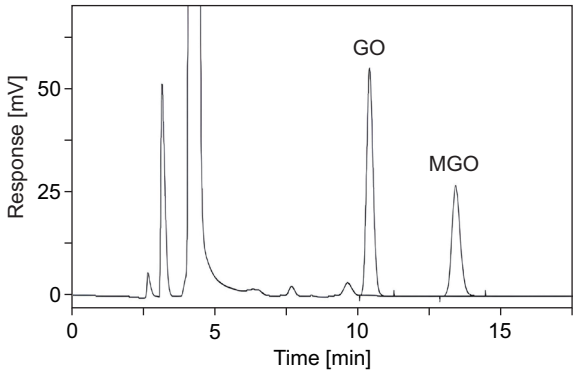

Fig. 1. HPLC chromatogram of glyoxal and methylglyoxal standards.

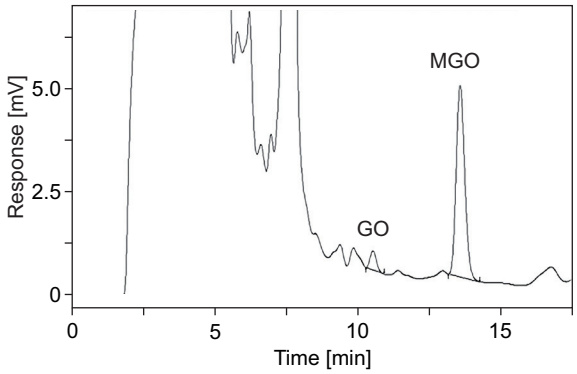

Fig. 2. HPLC chromatogram of glyoxal and methylglyoxal in sulfured dried apricot (sample No. 10).

Tab. 1. Sample types, measured amount of glyoxal, methylglyoxal, and free sugar content in sun-dried apricots.

Sample number	GO [mg·kg^{-1}]	MGO [mg·kg^{-1}]	Total GO + MGO [mg·kg^{-1}]	Fructose [g·kg^{-1}]	Glucose [g·kg^{-1}]	Saccharose [g·kg^{-1}]	Total sugar [g·kg^{-1}]
1	1.236 ± 0.056	11.502 ± 0.520	12.737 ± 0.576	1.226 ± 0.055	3.738 ± 0.169	1.047 ± 0.047	6.010 ± 0.272
2	0.040 ± 0.002	23.701 ± 1.072	23.741 ± 1.074	1.106 ± 0.050	3.897 ± 0.176	0.409 ± 0.018	5.412 ± 0.245
3	0.907 ± 0.041	10.415 ± 0.471	11.322 ± 0.512	1.226 ± 0.055	3.528 ± 0.160	1.764 ± 0.080	6.518 ± 0.295
4	1.086 ± 0.049	18.917 ± 0.856	20.003 ± 0.905	1.226 ± 0.055	4.316 ± 0.195	1.904 ± 0.086	7.445 ± 0.337
5	0.748 ± 0.034	7.664 ± 0.347	8.412 ± 0.381	1.136 ± 0.051	3.588 ± 0.162	1.754 ± 0.079	6.478 ± 0.293
6	1.475 ± 0.067	19.495 ± 0.882	20.970 ± 0.949	1.086 ± 0.049	3.977 ± 0.180	1.286 ± 0.058	6.349 ± 0.287
7	1.096 ± 0.050	10.923 ± 0.494	12.020 ± 0.544	1.176 ± 0.053	3.538 ± 0.160	2.302 ± 0.104	7.017 ± 0.317
8	0.937 ± 0.042	21.827 ± 0.988	22.764 ± 1.030	1.395 ± 0.063	4.037 ± 0.183	1.266 ± 0.057	6.698 ± 0.303
9	0.927 ± 0.042	11.422 ± 0.517	12.349 ± 0.559	1.106 ± 0.050	3.688 ± 0.167	1.565 ± 0.071	6.359 ± 0.288
10	0.787 ± 0.036	17.063 ± 0.772	17.850 ± 0.808	1.017 ± 0.046	4.136 ± 0.187	1.425 ± 0.064	6.578 ± 0.298
11	1.126 ± 0.051	8.661 ± 0.392	9.787 ± 0.443	0.997 ± 0.045	4.326 ± 0.196	0.857 ± 0.039	6.179 ± 0.280
12	0.857 ± 0.039	11.442 ± 0.518	12.299 ± 0.556	1.296 ± 0.059	4.236 ± 0.192	1.226 ± 0.055	6.757 ± 0.306
13	0.957 ± 0.043	9.757 ± 0.441	10.714 ± 0.485	1.326 ± 0.060	3.757 ± 0.170	1.365 ± 0.062	6.448 ± 0.292
14	0.648 ± 0.029	17.232 ± 0.780	17.880 ± 0.809	1.206 ± 0.055	3.708 ± 0.168	1.505 ± 0.068	6.419 ± 0.290
15	0.628 ± 0.028	7.993 ± 0.362	8.621 ± 0.390	1.226 ± 0.055	3.787 ± 0.171	1.734 ± 0.078	6.747 ± 0.305
16	0.887 ± 0.040	5.581 ± 0.253	6.468 ± 0.293	1.296 ± 0.059	3.538 ± 0.160	2.482 ± 0.112	7.316 ± 0.331
17	1.166 ± 0.053	6.518 ± 0.295	7.684 ± 0.348	1.156 ± 0.052	3.608 ± 0.163	1.694 ± 0.077	6.458 ± 0.292
18	1.086 ± 0.049	16.385 ± 0.741	17.472 ± 0.790	1.216 ± 0.055	4.027 ± 0.182	1.096 ± 0.050	6.339 ± 0.287
19	0.458 ± 0.021	0.488 ± 0.022	0.947 ± 0.043	1.395 ± 0.063	3.658 ± 0.165	1.505 ± 0.068	6.558 ± 0.297
20	0.887 ± 0.040	13.425 ± 0.607	14.312 ± 0.648	0.997 ± 0.045	3.787 ± 0.171	1.953 ± 0.088	6.737 ± 0.305
21	0.937 ± 0.042	3.997 ± 0.181	4.934 ± 0.223	1.206 ± 0.055	3.747 ± 0.170	1.993 ± 0.090	6.947 ± 0.314
22	0.598 ± 0.027	11.402 ± 0.516	12.000 ± 0.543	1.056 ± 0.048	3.309 ± 0.150	1.296 ± 0.059	5.661 ± 0.256
23	1.056 ± 0.048	11.123 ± 0.503	12.179 ± 0.551	0.867 ± 0.039	2.761 ± 0.125	2.432 ± 0.110	6.060 ± 0.274
24	0.857 ± 0.039	11.352 ± 0.514	12.209 ± 0.552	1.066 ± 0.048	4.615 ± 0.209	1.196 ± 0.054	6.877 ± 0.311
25	0.449 ± 0.020	15.050 ± 0.681	15.498 ± 0.701	1.266 ± 0.057	3.658 ± 0.165	2.183 ± 0.099	7.106 ± 0.322
26	1.595 ± 0.072	12.458 ± 0.564	14.053 ± 0.636	1.126 ± 0.051	3.767 ± 0.170	1.575 ± 0.071	6.468 ± 0.293
27	1.027 ± 0.046	10.106 ± 0.457	11.133 ± 0.504	1.096 ± 0.050	3.488 ± 0.158	0.957 ± 0.043	5.541 ± 0.251

Values are mean ± standard deviation (n = 3).
GO – glyoxal, MGO – methylglyoxal.

Tab. 2. Sample types measured amount of glyoxal, methylglyoxal, and free sugar content in sulfured-dried apricots.

Sample number	GO [mg·kg^{-1}]	MGO [mg·kg^{-1}]	Total GO + MGO [mg·kg^{-1}]	Fructose [g·kg^{-1}]	Glucose [g·kg^{-1}]	Saccharose [g·kg^{-1}]	Total sugar [g·kg^{-1}]
1	0.867 ± 0.039	27.000 ± 1.222	27.867 ± 1.261	1.146 ± 0.052	4.226 ± 0.191	0.904 ± 0.041	6.276 ± 0.284
2	0.110 ± 0.005	23.970 ± 1.084	24.079 ± 1.089	1.256 ± 0.057	4.555 ± 0.206	0.478 ± 0.022	6.289 ± 0.285
3	0.189 ± 0.009	80.581 ± 3.646	80.770 ± 3.654	1.654 ± 0.075	3.628 ± 0.164	1.186 ± 0.054	6.468 ± 0.293
4	0.787 ± 0.036	37.764 ± 1.709	38.551 ± 1.744	1.525 ± 0.069	4.485 ± 0.203	1.066 ± 0.048	7.076 ± 0.320
5	0.807 ± 0.037	30.000 ± 1.357	30.807 ± 1.394	1.355 ± 0.061	3.917 ± 0.177	0.548 ± 0.025	5.821 ± 0.263
6	0.179 ± 0.008	74.122 ± 3.354	74.302 ± 3.362	1.206 ± 0.055	3.747 ± 0.170	1.086 ± 0.049	6.040 ± 0.273
7	0.209 ± 0.009	7.422 ± 3.359	74.451 ± 3.368	1.435 ± 0.065	3.797 ± 0.172	1.276 ± 0.058	6.508 ± 0.294
8	0.269 ± 0.012	77.451 ± 3.504	77.720 ± 3.516	1.106 ± 0.050	4.545 ± 0.206	0.967 ± 0.044	6.618 ± 0.299
9	0.409 ± 0.018	33.289 ± 1.506	33.697 ± 1.525	1.316 ± 0.060	3.708 ± 0.168	0.738 ± 0.033	5.761 ± 0.261
10	1.176 ± 0.053	28.066 ± 1.270	29.242 ± 1.323	1.605 ± 0.073	4.894 ± 0.221	0.658 ± 0.030	7.156 ± 0.324
11	0.777 ± 0.035	33.378 ± 1.510	34.156 ± 1.545	1.495 ± 0.068	3.817 ± 0.173	0.987 ± 0.045	6.299 ± 0.285
12	0.140 ± 0.006	76.574 ± 3.464	76.713 ± 3.471	1.355 ± 0.061	4.276 ± 0.193	0.907 ± 0.041	6.538 ± 0.296
13	0.150 ± 0.007	129.427 ± 5.856	129.577 ± 5.862	1.585 ± 0.072	3.937 ± 0.178	1.027 ± 0.046	6.548 ± 0.296
14	0.738 ± 0.033	99.338 ± 4.494	100.075 ± 4.528	1.475 ± 0.067	4.555 ± 0.206	0.508 ± 0.023	6.538 ± 0.296
15	0.628 ± 0.028	94.673 ± 4.283	95.301 ± 4.312	1.455 ± 0.066	3.897 ± 0.176	0.837 ± 0.038	6.189 ± 0.280
16	0.877 ± 0.040	141.327 ± 6.394	142.204 ± 6.434	1.645 ± 0.074	4.017 ± 0.182	1.156 ± 0.052	6.817 ± 0.308
17	0.249 ± 0.011	14.950 ± 0.676	15.199 ± 0.688	1.455 ± 0.066	4.196 ± 0.190	1.306 ± 0.059	6.957 ± 0.315
18	0.199 ± 0.009	43.385 ± 1.963	43.584 ± 1.972	1.196 ± 0.054	4.515 ± 0.204	1.066 ± 0.048	6.777 ± 0.307
19	0.239 ± 0.011	55.783 ± 2.524	56.023 ± 2.535	1.814 ± 0.082	4.385 ± 0.198	0.578 ± 0.026	6.777 ± 0.307
20	0.409 ± 0.018	94.135 ± 4.259	94.544 ± 4.277	1.495 ± 0.068	4.585 ± 0.207	0.748 ± 0.034	6.827 ± 0.309
21	0.807 ± 0.037	30.956 ± 1.401	31.764 ± 1.437	1.694 ± 0.077	4.216 ± 0.191	1.086 ± 0.049	6.997 ± 0.317
22	0.289 ± 0.013	43.893 ± 1.986	44.182 ± 1.999	1.336 ± 0.060	4.336 ± 0.196	0.937 ± 0.042	6.608 ± 0.299
23	0.199 ± 0.009	49.664 ± 2.247	49.863 ± 2.256	1.625 ± 0.074	3.747 ± 0.170	0.369 ± 0.017	5.741 ± 0.260
24	0.827 ± 0.037	45.707 ± 2.068	46.534 ± 2.105	1.236 ± 0.056	3.797 ± 0.172	1.017 ± 0.046	6.050 ± 0.274
25	0.030 ± 0.001	59.611 ± 2.697	59.641 ± 2.698	1.535 ± 0.069	3.688 ± 0.167	1.136 ± 0.051	6.359 ± 0.288
26	0.857 ± 0.039	23.940 ± 1.083	24.797 ± 1.122	1.355 ± 0.061	3.399 ± 0.154	1.037 ± 0.047	5.791 ± 0.262
27	0.249 ± 0.011	35.103 ± 1.588	35.352 ± 1.599	1.276 ± 0.058	4.365 ± 0.198	0.817 ± 0.037	6.458 ± 0.292

Values are mean ± standard deviation (n = 3).
GO – glyoxal, MGO – methylglyoxal.

The lowest MGO content was determined in one sample of sun-dried apricots with 0.488 mg·kg^{-1}. The averages showed that sulfured-dried apricots contained less GO with 0.469 mg·kg^{-1} and had higher MGO content with 55.241 mg·kg^{-1}. As for sun-dried apricots, they had higher mean GO (0.906 mg·kg^{-1}) and less MGO means (12.070 mg·kg^{-1}) than sulfured-dried apricots.

Dried fruits have higher sugar content when compared to the same amount of fresh fruits [14, 15]. In our study, glucose and fructose, which are reducing sugars, ranged from 2.761 g·kg^{-1} to 4.894 g·kg^{-1} and from 0.867 g·kg^{-1} to 1.814 g·kg^{-1} in dried apricots, respectively. The non-reducing sugar saccharose was between 0.369 g·kg^{-1} and 2.482 g·kg^{-1} in dried apricots. Total sugar ranged from 5.412 g·kg^{-1} to 7.445 g·kg^{-1}. Comparing the glucose contents, fructose, and saccharose in the samples, glucose was higher in both sun-dried apricots and sulfured-dried apricots samples. In 20 out of 27 sun-dried apricot samples, saccharose content exceeded fructose levels. Correspondingly, the mean GO content in sun-dried apricots (0.89 ± 0.29 mg·kg^{-1}) was significantly higher than in sulfured-dried samples (0.44 ± 0.28 mg·kg^{-1}), as shown in Tab. 3 and Tab. 4. These findings suggest a potential relationship between higher saccharose content and increased GO formation in sun-dried apricots. Fructose content was consistently higher than saccharose in all sulfured-dried apricot samples. According to the mean values presented in Tab. 3 and Tab. 4, sulfured-dried apricots had a significantly higher average MGO content (54.72 ± 34.11 mg·kg^{-1}) compared to sun-dried apricots (12.48 ± 6.65 mg·kg^{-1}). Since fructose is a known precursor for MGO formation, this result suggests that the higher fructose content in sulfured apricots (1.43 ± 0.27 g·kg^{-1}) may contribute to the elevated MGO levels observed in this group. Similarly to fructose, the elevated glucose levels in the sulfured-dried apricots (Tab. 4) could also have contributed to the increased MGO content, because glucose is also a known substrate for MGO, but a less efficient one than fructose.

The lower saccharose content and higher glucose and fructose levels observed in sulfured-dried apricots are probably caused by the inversion of saccharose. This process may be facilitated by the decrease in pH during sulfurisation, leading to the hydrolysis of saccharose into glucose and fructose. Similar observations were reported by Karabulut et al. [16], Inserra et al. [17], and Özbek et al. [18], highlighting the role of sulfur treatment in the increase of glucose and fructose levels, subsequently providing the substrates available for both GO and MGO synthesis.

Drying apricots concentrates their sugar content, which may increase GO and MGO content throughout food processing and long-term storage, regardless of the group differences between the individual sugars.

The results summarised in Tab. 3 and Tab. 4

Tab. 3. Summary of glyoxal, methylglyoxal and free sugar content in sun-dried apricot samples (n = 27).

Parameter	Mean ± *SD* (*n* = 3)	Minimum	Maximum
GO [mg·kg^{-1}]	0.89 ± 0.29	0.45	1.60
MGO [mg·kg^{-1}]	12.48 ± 5.09	0.49	23.70
Total GO + MGO [mg·kg^{-1}]	13.37 ± 5.33	0.95	25.14
Fructose [g·kg^{-1}]	1.19 ± 0.19	0.87	1.40
Glucose [g·kg^{-1}]	3.72 ± 0.33	2.76	4.61
Saccharose [g·kg^{-1}]	1.39 ± 0.54	0.41	2.48
Total sugar [g·kg^{-1}]	6.46 ± 0.59	5.41	7.45

SD – standard deviation, GO – glyoxal, MGO – methylglyoxal.

Tab. 4. Summary of glyoxal, methylglyoxal and free sugar content in sulfured-dried apricot samples (n = 27).

Parameter	Mean ± *SD* (*n* = 3)	Minimum	Maximum
GO [mg·kg^{-1}]	0.44 ± 0.28	0.03	1.18
MGO [mg·kg^{-1}]	54.72 ± 32.18	7.42	141.33
Total GO + MGO [mg·kg^{-1}]	55.16 ± 32.45	7.43	142.20
Fructose [g·kg^{-1}]	1.39 ± 0.18	1.11	1.81
Glucose [g·kg^{-1}]	4.17 ± 0.33	3.39	4.89
Saccharose [g·kg^{-1}]	0.88 ± 0.32	0.37	1.28
Total sugar [g·kg^{-1}]	6.31 ± 0.55	5.74	7.16

SD – standard deviation, GO – glyoxal, MGO – methylglyoxal.

demonstrate notable differences between sun-dried and sulfured-dried apricot samples regarding GO, MGO, and sugar contents. Sun-dried apricots exhibited relatively low levels of GO (mean 0.89 mg·kg^{-1}) and MGO (mean 12.48 mg·kg^{-1}). In contrast, sulfured-dried apricots showed significantly higher MGO contents (mean 54.72 mg·kg^{-1}), with GO levels generally lower (mean 0.44 mg·kg^{-1}) compared to sun-dried samples. Total GO and MGO content followed a similar trend, with sulfured samples having substantially elevated values. Regarding free sugars, fructose and glucose contents were slightly higher in sulfured apricots, while saccharose levels were lower compared to sun-dried samples. Overall, total sugar content was comparable between the two drying methods. These differences likely reflect the impact of sulfur treatment on the formation of reactive carbonyl compounds, such as MGO, and alterations in sugar profiles during drying and preservation.

Importantly, sulfured-dried apricots contained an average of 5 times more MGO than sun-dried apricots, while sun-dried apricots contained approximately 2 times more GO than sulfured-dried apricots. Chemical and thermal pretreatment practices are widely used in preserving dried fruit quality. Although practical, chemical applications such as dipping fruit into sulfite solutions are not sustainable pre-treatment ways. The use of sulfur dioxide in foods has been banned in many countries due to its health-related side effects. Ottum and Mistry [19] noted that lysine, arginine, and sulfur-containing amino acids are involved in forming exogenous AGEs and are particularly sensitive to glycoxidation. Apart from the Maillard reaction, dicarbonyl compounds can also be formed by the degradation of sugars and autoxidation without the presence of proteins [20]. The formation of MGO, the most common α-dicarbonyl compound, was determined during the heat processing of glucose, fructose, maltose, and maltulose. However, the amount of MGO obtained from monosaccharides was significantly higher than from disaccharides. This formation of α-dicarbonyl by the breakdown of sugars can occur under all food processing-related conditions, although alkali conditions highly prefer them [20].

High fructose corn syrup (HFCS) has been widely used by the food and beverage industry for decades due to its low cost [21]. Besides this widespread use, HFCS has also been reported to contain significant amounts of sugar degradation products such as GO, MGO, and 3-deoxyglucosone. These degradation products have been identified and measured, especially in soft drinks, which have high HFCS content and are exposed to various processes in industrial production [21]. A study by Gensberger et al. [22] found that the total α-dicarbonyl concentration in 25 soft drinks ranged from 0.3 μg·ml^{-1} to 116 μg·ml^{-1}and was significantly higher in those sweetened with HFCS alone than in others (HFCS-saccharose or saccharose alone). Thus, it was stated that the sweetener used was influential in the amount of total α-dicarbonyls [22]. Our findings suggest that the higher MGO content of sulfured-dried apricots can be explained by their higher fructose levels compared to the sun-dried apricots.

Micronutrients such as polyphenols, vitamins A, B1, B6, C, and E have been associated with reducing AGEs [23]. In one study, catechins and proanthocyanidins reduced the amount of MGO, GO, and N-ε-carboxymethyl lysine in enriched bread [24]. Each dried fruit has unique phenolic properties. Because of their high polyphenol content, dried fruits are an important source of antioxidants in the diet, contributing to the reduction of oxidative stress and thus preventing oxidative damage to critical cellular components [25, 26]. Dried apricots contain high amounts of carotenoids and organic acids. These contents may decrease during the drying and storage processes. The sulfurisation process applied to apricots before drying is effective in preserving the polyphenol content by inhibiting polyphenol oxidase as well as preserving the yellow colour of apricots by preventing non-enzymatic reactions in apricots [25]. In a study by Salur-Can et al. [26], the effect of sulfur dioxide concentration on β-carotene and organic acids in dried apricots during storage was investigated. In the study, it was observed that as the sulfur dioxide concentrations increased, the content of some organic acid varieties increased while some decreased. It was determined that the β-carotene amount was positively affected by the increase in sulfur dioxide up to a certain level. However, the same effect was not observed in a further increase [26]. In the present study, the GO content of sun-dried apricots was higher than that of sulfured-dried apricots. In comparison, the MGO content was significantly lower (2 times more and 5 times lower, respectively). We thought that the high GO content in sun-dried apricots and the high MGO content in sulfured-dried apricots might be due to the varying amounts of different organic acids, β-carotene and sulfur dioxide in dried apricots.

Desired or undesired chemical or biochemical reactions can occur in the thermal processing of fruits. Drying refers to removing moisture from material to reduce microbial activity and

food spoilage and to extend shelf life. Fruits are dried using different methods such as microwave drying, oven, cabinet tray, solar, and freeze-drying. Conventional hot air drying of fruits includes the use of dryers such as a continuous belt, tunnel, cabinet, and kiln. KALRA and BHARDWAJ [27] have revealed solar dehydration research for fruits and vegetables. They determined that the dehydration model with a high temperature at 70–75 °C is more efficient than the dehydration model with a low temperature at 50–55 °C. BHUTANI and SHARMA [28] reported drying apricots processed faster across a flow dehydrator than in open sun-drying. Sun-drying is the cheapest way to dry fruit in most developing countries. It is applied in two ways: direct or indirect. The direct method, commonly known as sun-drying, involves placing it in the open air, where solar radiation is used as an energy source to dry the fruit product directly. The indirect method means using mechanical solar dryers based on solar energy to heat the drying air and then flow in or on the product with natural or forced convection means [29, 30].

Maillard reaction occurs at above 50 °C and pH 4–7 [31]. As we mentioned above, the processing conditions of dried fruits are above 50 °C. In addition, the degree of glycation accelerates with increasing processing temperature [11]. Therefore, increasing the processing temperature increases the formation of MGO. As mentioned, the Maillard reaction is initiated between reduced sugar and protein above 50 °C and leads to Amadori products [31]. However, Amadori products can be degraded to α-dicarbonyl compounds due to prolonged storage, cooking time, and increased cooking temperature [11, 7]. Comparing the GO and MGO amounts between dried apricots, the GO content of sun-dried apricots and the MGO content of sulfured-dried apricots were higher. This difference may be due to sugar content, drying methods, the temperature of the drying environment, bioactive components, storage times, storage temperature, and reactions resulting from exposure to components such as sulfur dioxide. In terms of sugar content, a higher correlation was stated between dicarbonyl compounds and glucose and fructose than saccharose [32, 33]. In addition, in a study by HAMZAOĞLU et al. [32], it was observed that while Maillard reaction did not occur during the drying process in sulfured-dried apricots, Maillard reaction could occur depending on the temperature and time during storage [32]. Therefore, in our study, it is thought that the higher MGO content of sulfured-dried apricots may be due to the sulfurisation process being applied at different temperatures and the conditions that occur during the subsequent storage process.

Studies on dietary AGE intake restriction are generally given priority in detecting the AGE content of foods. While determining this content, the most abundant dicarbonyls in processed foods and our body, such as GO and MGO, are taken as references. Besides being rich in fat and protein, cooking methods, such as grilling, roasting, baking, frying, and cooking conditions, such as increased cooking time, high temperature, low humidity, high pH, and adding extra oil play an essential role in AGE formation [11]. For example, in a study carried out by URIBARRI et al. [11], the dietary advanced glycation end-products amount of roasted foods at dry heat was higher than that of the raw ones in the oil seeds, such as almonds and cashews, peanuts, sunflower seeds. Also, in the same study, it was found that raw fruits have lower dietary advanced glycation end-product content than dried fruits.

MGO is a highly reactive dicarbonyl compound compared to GO. It reacts with lipids, DNA, and the residues of proteins (through lysine, cysteine, and arginine), conducting the formation of AGEs [34]. In some clinical investigations, an AGE-restricted diet has been related to decreased circulating levels of AGEs and complications of diabetes mellitus and Alzheimer's disease [35]. High amounts of MGO cause inhibition of (IRS)-1 and PI3K/Akt pathway, leading to insulin resistance and decreased insulin secretion in beta cells [34]. MGO concentration in plasma has been found to be very high in individuals with Type 1 and Type 2 diabetes. In an animal study, administration of MGO to rats caused beta cell dysfunction and insulin resistance. The MGO level in diabetic patients was between 0.115–0.228 $\mu g \cdot ml^{-1}$, while in healthy subjects it was 0.025–0.065 $\mu g \cdot ml^{-1}$ [36]. DEGEN et al. [37] reported that the estimated range of dietary MGO intake in people consuming sugar-rich products is between 5 mg per day and 20 mg per day. The accumulation of α-dicarbonyls can cause cellular damage by reacting with proteins [23]. As mentioned above, MGO is a very reactive α-dicarbonyl compound formed in the harmful end AGEs. Therefore, excessive consumption of foods with high amounts of MGO can cause many chronic diseases. Our results show that both sun-dried apricots and sulfured-dried apricots contain precursors of harmful AGEs. Therefore, monitoring and reducing AGE formation in foods during food processing and restricting intake of dietary AGEs is essential in preventing the harmful effects of AGE on health.

Moreover, it is important to note that indivi-

dual susceptibility to dietary AGEs varies depending on genetic factors, metabolic health, and gut microbiota composition. While apricots contain GO and MGO precursors, the actual impact on human health depends on overall dietary patterns and consumption levels. Future studies should focus on the bioavailability of these compounds from dried fruits and their metabolic fate in the human body to better understand their potential health risks and benefits.

CONCLUSIONS

In this study, the amounts of glucose, fructose, saccharose sugars, and GO and MGO, which are the two leading AGE precursors, were determined in sun-dried and sulfured-dried apricots. The formation of GO and MGO occurs as a result of Maillard reaction, lipid peroxidation, sugar degradation, and autoxidation during food processing and long-term storage. Sun-dried apricots with high glucose and saccharose content contained higher GO levels, while sulfured-dried apricots with high glucose and fructose content contained higher MGO amounts. Furthermore, it was observed that sulfured-dried apricots had a significantly higher MGO average. In this study, we observed that food processing temperature, processing time, storage time and addition of sulfite solution, especially sugar concentration, affected the formation of MGO and GO in processed dried apricots. Finally, this investigation revealed that the sugar content and type in processed dried apricots might encourage the production of α-dicarbonyl compounds. The accumulation of these AGEs in the human body endangers human health. The increased level of GO and MGO in plasma may cause diabetic complications, atherosclerosis, various types of cancer, and Alzheimer's disease. An AGE-restricted diet can reduce the potential health risks associated with AGEs. Thus, it is recommended that these products be processed using methods that prevent harmful AGE formation.

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