Comprehensive evaluation of physicochemical and bioactive properties of tahini–coffee beverages with chemometric approach: effect of roasting degree on *in vitro* bioaccessibility

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Abstract

In this study, a novel tahini-based coffee beverage model was developed to investigate the combined effects of different thermal treatment levels of tahini (roasted and double-roasted) and Colombian coffee (medium- and dark-roasted) on the physicochemical, sensorial, and bioactive properties of beverages during *in vitro* gastrointestinal digestion. The primary aim was to evaluate tahini as a nutritious, plant-based milk alternative in functional coffee beverage formulations. The beverages contained 1.43–2.08% proteins, 2.37–3.05% lipids, and 3.74–6.84% total sugar, with caffeine levels ranging from 328.05 to 372.53 mg/L. Double-roasting resulted in reduced protein content by 15% and 31.25% in beverages prepared with medium- and dark-roasted coffees, respectively. Total phenolic content decreased during the gastric phase but increased under intestinal conditions, compared to undigested samples. Total antioxidant capacity was significantly affected by roasting intensity and digestion stage ($P < 0.05$), with the overall values increasing after digestion. Chemometric analyses clearly differentiated the samples according to roasting level. Overall, the results suggest that tahini-based milk may represent a promising ingredient for the development of plant-based coffee beverages, although further studies are required to confirm its functional and commercial potential.

Keywords: caffeine; coffee; *in vitro* gastrointestinal digestion; phenolics; roasting; tahini

Introduction

Coffee, one of the most extensively consumed beverages globally, is a significant source of bioactive constituents, including phenolic acids, such as chlorogenic, caffeic, and gallic acids, and flavonoids, such as epicatechin, quercetin, and kaempferol. These compounds are primarily responsible for the antioxidant and anti-inflammatory effects attributed to coffee (Bastian *et al.*, 2021). The sensory attributes and chemical profile of coffee are substantially affected by variables such as geographic origin, processing techniques, and roasting parameters. During roasting, the formation of melanoidins (brown, nitrogen-containing heterogeneous polymers produced in the final stages of the Maillard reaction) and volatile compounds—crucial for the beverage's distinctive aroma and flavor—occurs via the Maillard reaction. However, exposure to high temperatures or prolonged roasting process can alter the biochemical properties of coffee, leading to damage or transformation of some phenolic

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compounds. Therefore, roasting process parameters in production of coffee are very important for the final quality of product (Wu *et al.*, 2022b).

Ready-to-drink (RTD) coffee beverages have gained significant popularity because of their convenience and extended shelf life. Traditionally, these products are formulated with coffee extracts supplemented with sugar and/or milk. However, high sugar intake is linked to various metabolic disorders, including obesity, diabetes mellitus, and hypertension (Boileau *et al.*, 2012). With increase in consumer health consciousness, there has been a discernible shift toward low-sugar or sugar-free formulations, aligning with European Union (EU) regulations that promote the use of natural sweeteners and sugar substitutes (Carbonell-Capella *et al.*, 2015). Within this framework, apple juice and particularly apple juice concentrate have garnered interest because of their ability to naturally impart sweetness, serve as a carbohydrate-based energy source, and act as alternatives to conventional sucrose, because of their intrinsic content of natural sugars, such as fructose, glucose, and sucrose (Esperança *et al.*, 2025).

The use of plant-based milk alternatives is becoming increasingly common in RTD coffee formulations in parallel to the increasing consumer demand for these beverages, which are rapidly gaining popularity, especially among franchise coffee sellers (Halabi *et al.*, 2024; Plamada *et al.*, 2023). This surge is primarily driven by factors such as lactose intolerance, milk allergies, adoption of vegan diets, and a growing demand for sustainable and functional food products. While typical plant-based milk alternatives include extracted milk of soy, almond, oats, and coconut, the market for tahini-based milk alternatives (TBMAs) has remained relatively underexplored despite its potential. Given its compositional attributes, tahini presents a promising raw material for developing stable, nutritious, and functional plant-based beverages (Plamada *et al.*, 2023; Rizki *et al.*, 2015).

Despite the growing body of research on plant-based milk alternatives in coffee systems, the existing studies have predominantly focused on conventional sources, such as soy, almond, oats, and coconut, mainly addressing sensory acceptability, physicochemical compatibility, and consumer preferences. However, these systems often face limitations related to nutritional density, stability, and functional bioactive composition. In particular, there is a notable lack of studies investigating alternative plant matrices with inherently high lipids, proteins, and antioxidant contents as well as their behavior under gastrointestinal digestion conditions.

Compared to widely used plant-based milk alternatives, such as oats, almond, and soy-based systems, tahini offers a distinct compositional advantage because of its higher protein content and lipid-rich structure. While many oats- and almond-based beverages are often characterized by relatively low protein levels and diluted nutrient density after processing, tahini retains a more concentrated profile of proteins, unsaturated fatty acids, and bioactive compounds.

This compositional richness influences not only the nutritional value but also the physicochemical behavior and extraction dynamics of coffee-based systems. Therefore, the use of tahini as a plant-based milk alternative provides a differentiated approach compared to conventional plant-based coffee beverages.

Tahini, characterized by its rich composition of unsaturated lipids, proteins, lignans, and phenolic compounds, represents a promising yet underexplored matrix for developing plant-based coffee beverages. Unlike widely studied plant-based milk alternatives, tahini offers a unique compositional profile that influences not only the nutritional and sensory properties but also the bioaccessibility of bioactive compounds within complex beverage systems.

Therefore, the novelty of the present study lies in the: (i) utilization of tahini as a unconventional plant-based milk alternative in coffee beverages, (ii) simultaneous evaluation of roasting level of both coffee and tahini as a combined process variable, (iii) investigation of *in vitro* gastrointestinal bioaccessibility of phenolics and antioxidant capacity within this composite matrix, and (iv) application of chemometric approaches (principal component analysis [PCA] and hierarchical cluster analysis [HCA]) to comprehensively interpret multidimensional dataset. To the best of our knowledge, no previous study has systematically addressed these aspects within a unified framework.

Tahini, also known as sesame paste, is derived from sesame seeds of *Sesamum indicum* L., which belongs to the family Pedaliaceae. *S. indicum* is an annual oilseed crop of Asia and Africa, and is widely cultivated across tropical and subtropical zones (Wei *et al.*, 2022). Currently, major producers include India, China, Myanmar, and Türkiye. The traditional manufacturing process of tahini involves cleaning sesame seeds, removing their husks, and roasting of seeds and grinding them into an oil-rich paste. The extent of roasting significantly influences sensory attributes, such as aroma and color, as well as the nutritional profile of the final product (Karakuş and Yaşar, 2025).

Based on its nutritional profile, tahini predominantly maintains a high lipid content, with a favorable lipids profile, with moderate levels of protein and

carbohydrates; it also retains various antioxidants and micronutrients. The ultimate compositional characteristics of tahini are influenced by the factors such as seed quality, processing parameters, and, notably, the degree of roasting. The roasting process enhances both development of aroma and flavor attributes; however, it concurrently impacts the stability, concentration, and structural integrity of bioactive constituents, especially phenolic compounds and unsaturated fatty acids. Several studies have documented a reduction in total phenolic content (TPC) attributable to thermal degradation or structural modifications induced by exposure to high temperatures, whereas certain studies have suggested that moderate roasting may initially augment antioxidant capacity prior to more intense roasting resulting in declined antioxidant content (Akele *et al.*, 2024; Balcázar-Zumaeta *et al.*, 2025).

This study responds to the growing demand of dairy-, lactose- and gluten-free plant-based beverages, particularly suitable for people with lactose intolerance, milk allergies, or consuming vegan/vegetarian diets. It is also suitable for people looking for functional, low-sugar and health-promoting beverages. Based on the natural sweetness derived from fruit sugars and without added sucrose, the developed formulation offers an easily digestible, nutrient-rich, and sustainable beverage alternative. For this purpose, TBMAs prepared from the coffee extracts of medium- and dark-roasted Colombian coffee beans and roasted and double-roasted sesame seeds were produced. The research comprehensively evaluates the physicochemical and functional properties and sensory profiles of the formulated beverages to determine their overall quality. The total antioxidant capacity (TAC) and TPC and *in vitro* bioaccessibility of the beverages were evaluated by 2,2-diphenyl-1-picrylhydrazy (DPPH), ferric reducing antioxidant power (FRAP), and cupric reducing antioxidant capacity (CUPRAC) assays. In addition, the effect of formulations on sensory attributes, such as taste, aroma, and bitterness, was systematically evaluated. Multivariate statistical techniques, such as PCA and HCA, were used to interpret multidimensional data in a holistic manner.

The findings are expected to contribute to the scientific literature by providing a healthy alternative to RTD beverages and to be a reference source for future industrial-scale product development studies. Although oats-, almond-, and soy-based beverages dominate the market currently, sesame-based systems remain underexplored despite their rich composition in proteins, unsaturated lipids, minerals, lignans, and phenolic compounds. To our knowledge, no previous study has systematically evaluated a tahini–coffee beverages by simultaneously examining degree of roasting, *in vitro* bioaccessibility, sensory attributes, and chemometric discrimination. Therefore, this study provides a novel strategy for developing nutrient-dense, plant-based coffee beverages.

Materials and Methods

Materials

Tahini (Harras, special brand; roasted [120°C, 120 min] and double-roasted [150°C, 150 min]), apple juice concentrate (Essen Organik, special brand) used as a sweetener, and citric acid (Alfasol, food grade) were purchased from a local market in Bursa, Türkiye. Medium-roasted (200°C, 11 min) and dark-roasted (210°C, 12 min) Colombian coffee was sourced from a local coffee producer (A Roasting Lab, Bursa, Türkiye). Coffee varieties used in the study are 100% Arabica coffee of the Caturra and Costilla. These varieties were harvested at an altitude of 1800–1850 m. All tahini samples were obtained from the same production batch to ensure consistency.

All raw materials were stored under controlled conditions prior to analysis to prevent compositional changes.

Methods

Production

In this research, a novel functional beverage was formulated through the combination of medium- and dark-roasted coffee extracts with TBMA produced from both roasted and double-roasted tahini. The production flow chart of tahini–coffee beverages is shown in Figure 1.

According to preliminary trials, TBMA was obtained from each tahini variety with 23% (w/v) tahini content. For this purpose, weighed tahini was added to bottled water at 95 ± 5°C and mixed effectively with a blender (1000 W, BRAUN Multiquick 5, MQ5275BK, Neu-Isenburg). Medium- and dark-roasted crunched coffee varieties were brewed (95 ± 5°C for 3 min) using a drip filter coffee machine (Arçelik, Fk 6910, Türkiye) to obtain coffee extracts with a coffee content of up to 4% (w/v).

Medium- and dark-roasted coffee extracts were mixed with TBMA at a ratio of 3:1 (v/v) to formulate mixtures. The mixtures were kept at room temperature (25 ± 2°C) and apple juice concentrate (10% [w/v]) was added. Citric acid (0.15%), which plays an important role in balancing taste and aroma, was added as an acidity regulator. The resulting beverages were filled into 200-mL glass bottles, capped, and pasteurized at 98°C for 15 min.

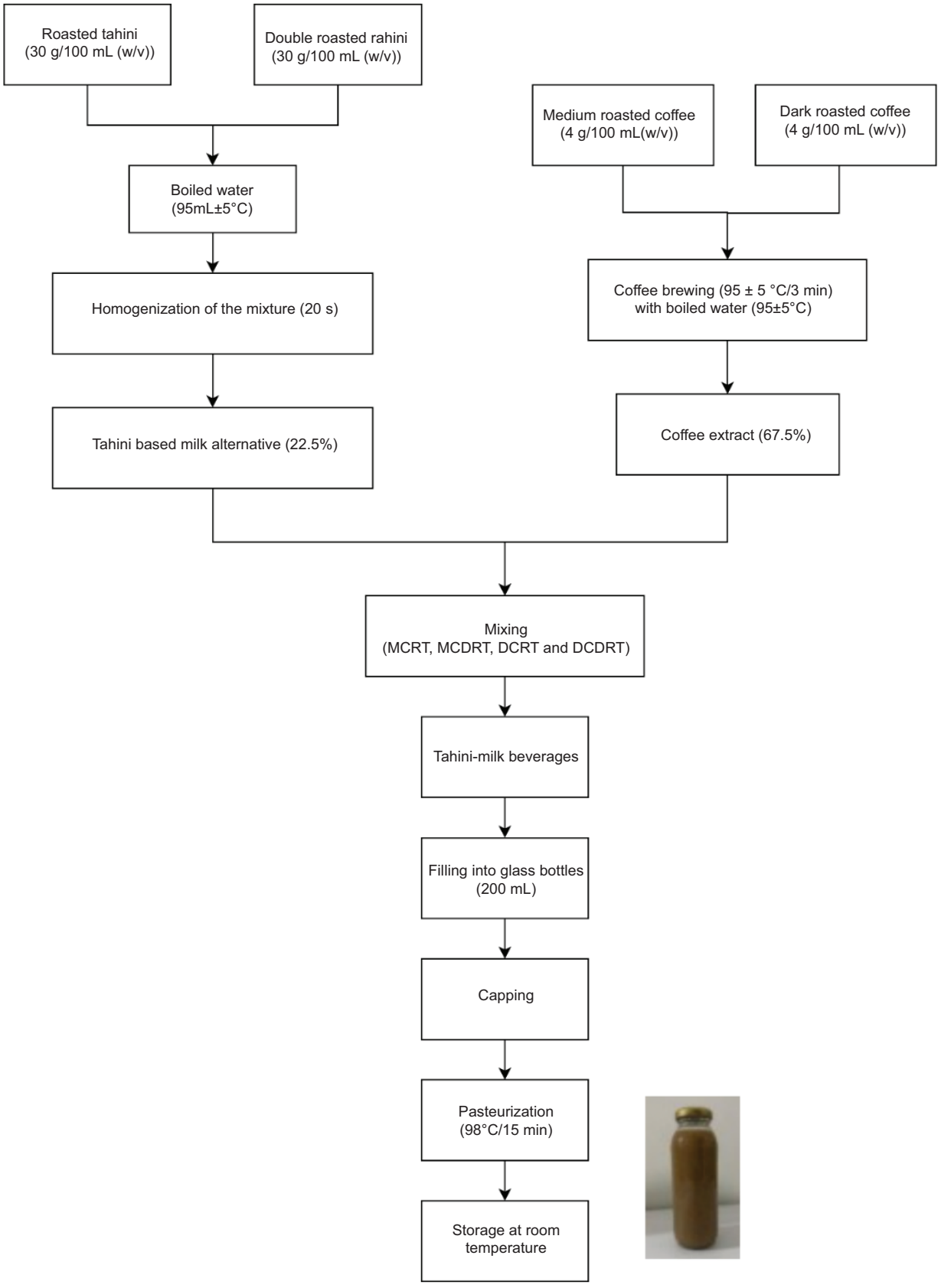

Figure 1. Production flow chart of tahini–coffee beverages.

The selection of roasting conditions for both coffee and tahini was based on commonly applied industrial- and literature-reported roasting ranges, where medium- and dark-roasting levels are known to influence significantly the physicochemical and bioactive properties of coffee and oilseeds. Previous studies have demonstrated that roasting temperature and time are critical parameters affecting the formation and degradation of phenolic compounds, melanoidins, and antioxidant capacity in coffee systems (Balcázar-Zumaeta *et al.*, 2025).

Similarly, formulation ratios between tahini-based milk alternative and coffee extract (3:1, v/v) and tahini concentration (23%, w/v) were determined based on preliminary trials to ensure optimal physicochemical stability, sensory acceptability, and process feasibility. These ratios were selected to provide a balanced matrix that allows the evaluation of interactions between coffee- and tahini-derived components without phase separation or excessive viscosity.

Analysis

Physicochemical Characteristics: Total soluble solids, expressed as °Brix, of tahini–coffee beverages were determined at 20 ± 0.5°C using a digital refractometer (RFM960; Bellingham & Stanley Ltd., Tunbridge Wells, UK).

Samples' pH was measured using a calibrated pH meter (Seven Compact, Mettler Toledo International Inc., Switzerland).

Total acidity (TA) was assessed by potentiometric method (by titrating 5.00 ± 0.01 mL of tahini–coffee beverage with 0.1-N NaOH solution to an endpoint of pH 8.2) and the results were expressed as a percentage of citric acid according the method described by Batali *et al.* (2021).

Volor parameters of beverage samples were determined using a Minolta CM-5 spectrophotometer (Minolta; Osaka, Japan), which recorded the L*, a*, and b* color coordinates on sample surface points (Minolta, 2013). Measurements were based on the CIE color system, where L* denotes lightness (darkness–lightness), a* represents green–red axis, and b* indicates blue–yellow axis. For each sample, the final color values were expressed as the average of reflectance measurements taken at three different surface points. Chroma (C*) represents the degree of color saturation, ranging from 0 (dull) to 60 (vivid), while hue angle (h°) defines color tone, where 0° corresponds to red, 90° to yellow, 180° to green, 270° to blue, and 360° to red again (Deniz and Suna, 2025).

Total protein analysis: Protein analysis was conducted using the Dumas method, which involves measuring nitrogen in gas phase, following combustion. Sample combustion occurs in a pure oxygen environment at temperatures ranging from 800°C to 950°C within a flame. The residual gases produced during combustion are collected in filters for disposal, while the conversion of nitrogen oxides to nitrogen is facilitated by the removal of oxygen using hot copper. Consequently, the nitrogen content, carried by helium, is quantified through thermal conductivity measurements. Protein concentration is subsequently calculated based on nitrogen content, utilizing a conversion factor as established by Roland *et al.* (2023).

Total lipid content analysis: Total lipid content in samples was analyzed using the NMKL 160 Gravimetric Method (Aktaş and Aydin, 2024). This procedure involved boiling of samples in a diluted hydrochloric acid (HCl) solution to liberate bounded lipids and converting fatty acid salts into free fatty acids. Following this treatment, the resulting residue was subjected to extraction with either petroleum ether or hexane after undergoing filtration and drying. The solvent was subsequently removed through distillation, and mass of the remaining residue was determined. The lipids content of the samples was expressed as a percentage by weight (% lipids).

Total sugar analysis: Sugar was analyzed using the Lane–Eynon method, which is a titrimetric analytical procedure. Total sugar content is determined based on the reduction of copper (II) ions to copper (I) ions by reducing sugars. In this context, 50 mL of the previously prepared filtrate was transferred into a 100-mL volumetric flask, followed by the addition of 5 mL of concentrated HCl. The mixture was subjected to inversion in a water bath at 67–70°C for 5 min. After rapid cooling, the solution was neutralized by titrating with 5-N NaOH in the presence of phenolphthalein indicator until a faint pink color was obtained; then the solution was made up to 100 mL with distilled water, and filtered.

For titration, 5 mL of Fehling A solution and 5 mL of Fehling B solution were heated to boiling in an Erlenmeyer flask. Once boiling commenced, several drops of methylene blue indicator were added, and the sample filtrate was titrated until a brick-red color was obtained. Formation of red copper (I) oxide (Cu_2O) precipitate confirmed the reduction of Cu^{2+} to Cu^{+} by the reducing sugars present in the sample, indicating the completion of the reaction. Based on titrant consumption, the total sugar content was calculated and expressed as a percentage of reducing sugars in the sample (Afshari *et al.*, 2022).

Total caloric value calculation: The total caloric content of samples is calculated by first analyzing macronutrient

levels (proteins, lipids, and sugars) to obtain the amounts of each component, multiplying these amounts by their energy conversion factors, and then summing these energy values. According to the conversion factor commonly used in literature, the total caloric value of protein was determined as 17 kJ/g (4 kcal/g), of lipids as 37 kJ/g (9 kcal/g), and that of sugars as 17 kJ/g (4 kcal/g) by using the following calculation formula:

Total caloric value (kcal) = (Total protein × 4.0) + (Total lipid × 9.0) + (Total sugars × 4.0) (Food and Agriculture Organization [FAO], 2003).

Caffeine analysis using high-performance liquid chromatography (HPLC): Caffeine was analyzed using HPLC DAD–1260 (INFINITY). Instrumental method was used, and the sample was dissolved in water, filtered, and injected into the device. Absorbance at a wavelength of 272 nm was monitored in caffeine analysis. In this method, calculations were performed based on the principle of comparing the sample's peak area with calibration curve (Mirza *et al.*, 2021). Chromatograms for the standard and samples are shown in Supplementary Figure S1 (in the supplementary material).

Total phenolic content analysis: Total phenolic content of tahini–coffee beverages was assessed utilizing a Ultraviolet (UV)-visible spectrophotometer (UV-1800, Shimadzu) and calculated according to the Folin–Ciocalteu method. Specifically, a mixture comprising 100 µL of the beverage extract and 0.75 mL of Folin–Ciocalteu reagent (diluted at a ratio of 1:10) was incubated for 5 min. Subsequently, 0.75 mL of 6% sodium carbonate solution was added into test tubes. Then the samples were allowed to stand at an ambient temperature for 90 min. The resulting TPC was expressed as milligrams of gallic acid equivalent (GAE)/100 g of dry matter (DM), as outlined by Durgut Malçok *et al.* (2025).

Total antioxidant capacity analysis: In this investigation, TAC was assessed utilizing DPPH, FRAP, and CUPRAC assays. For DPPH assay, 0.1 mL of the sample was combined with 3.9 mL of DPPH solution and subjected to vortex mixing for 30 s using a Vortex Mixer Classic (Velp Scientifica, Usmate, Italy). The test tubes were subsequently incubated in the dark at ambient temperature for 30 min. A calibration curve for trolox (R^2 = 0.9997) was established by measuring reduction in absorbance of DPPH solution in the presence of varying concentrations of trolox (10–100 µmol/L) (Kumaran, 2006).

In the case of FRAP assay, 3 mL of freshly prepared FRAP reagent was mixed with 300 µL of distilled water and 100 µL of either the sample or a blank control. Samples and blank control were incubated at 37°C for 30 min, after which the absorbance was measured immediately at 595 nm. The results were derived from a calibration curve, expressed as micromoles of trolox equivalent (TE)/g DM for beverages (R^2 = 0.9934) (Özkan-Karabacak *et al.*, 2023).

For the CUPRAC method, 100 µL of the sample was combined with 900 µL of distilled water and CUPRAC reagent comprising equal parts of $CuCl_2$, neocuproine, and ammonium acetate solution. The absorbance of the mixture was recorded at 450 nm, following a 30-min incubation period (R^2 = 0.9933). The results were expressed as µmol TE/g DM (Apak *et al.*, 2004). Antioxidant capacity values (DPPH, FRAP, and CUPRAC) were expressed on DM basis to eliminate the influence of moisture content and ensure comparability between samples.

In vitro gastrointestinal digestion: The beverage samples underwent *in vitro* gastrointestinal digestion following the protocol defined by Minekus *et al.* (2014), with specific modifications. This digestion process replicated both gastric and intestinal phases. In the gastric phase, a mixture was prepared that included simulated gastric fluid, porcine pepsin solution, and calcium chloride. The pH of this solution was adjusted to 3 adding HCl, and the mixture was incubated at 37°C for 2 h in a shaking water bath. At this stage, 4-mL aliquots were extracted from each test tube. After the gastric phase, the resultant residue was combined with simulated intestinal fluid, pancreatin solution, and bile solution for intestinal phase. The pH was subsequently adjusted to 7.0 using NaOH, and this mixture was incubated at 37°C for additional 2 h in a shaking water bath. Following incubation, the mixture was subjected to centrifugation and filtration, and the supernatant was collected. The samples obtained from both gastric and intestinal digestion phases were stored at –20°C for further analysis. These extracts were subsequently assessed for their TPC and TAC.

Sensory analysis: Seven panelists from the Department of Food Engineering at Bursa Uludağ University participated in the sensory evaluation of tahini–coffee beverage samples. The panelists were selected based on their familiarity with and regular consumption of coffee and plant-based beverages and their willingness to participate in sensory evaluation studies. Although the panel size was limited, it is consistent with exploratory sensory analyses commonly employed in academic product development studies.

Prior to the evaluation, all panelists were informed about the evaluation procedure and the sensory attributes to be assessed. Each sample was assigned a unique three-digit code for identification, and the assessment was conducted under controlled conditions. The evaluation

was performed using a five-point hedonic scale, ranging from 1 (dislike extremely) to 5 (like extremely), to reflect consumer-oriented perception, rather than trained descriptive profiling.

All sensory analyses were carried out in accordance with relevant standards of the International Organization for Standardization (ISO; (2006, 2011, 2017a, 2017b) to ensure methodological consistency and reliability. The panelists evaluated all samples based on color, odor, taste, coffee aroma, tahini aroma, bitterness, and the overall acceptability. To ensure statistical robustness, the obtained data were analyzed using Analysis of Variance (ANOVA), followed by Duncan's multiple range test, to determine significant differences between samples ($P < 0.05$).

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics version 23. To identify significant differences between mean values at a significance level of 5%, both ANOVA and Duncan's multiple range test were conducted. Each analysis was conducted in triplicate, and the results were reported as mean values accompanied by their respective standard deviations. In this study, multivariate data analysis techniques, specifically PCA and HCA, were utilized to explore data patterns and assess similarities and differences among samples. Prior to PCA, the dataset was standardized to eliminate scale differences among variables. All statistical analyses were performed using IBM SPSS Statistics (version 28; Chicago, IL, USA) and the Minitab Statistical Software (version 21; State College, PA, USA).

Each analytical measurement was performed in triplicate for each replicate sample, and these were considered as analytical replicates to account for instrumental and methodological variability. The mean values of analytical replicates were used for statistical analysis. This approach allows the distinction between biological/process variability and analytical variability, thereby improving the reproducibility and robustness of results.

Results and Discussion

Physicochemical characteristics

The physicochemical properties and color characteristics of the beverages are presented in Table 1. The highest °Brix value (7.46) was observed in the dark-roasted coffee extract + double-roasted tahini (DCDRT) sample and the lowest value was demonstrated in the medium-roasted coffee extract + roasted tahini (MCRT, 6.36 ± 0.05) sample ($P < 0.05$).

Similarly, results indicated that the °Brix values of functional beverages generally traversed from 6.20 to 7.00 (Durgut Malçok *et al.*, 2025), approximately 8 (Suna *et al.*, 2018), and in case of coffee extracts drawn from roasted beans subjected to varying roasting temperatures and durations, the values ranged between 6 and 8 (Balcázar-Zumaeta *et al.*, 2025).

Increasing roasting intensity led to higher °Brix values in both tahini and coffee-based formulations, potentially because of enhanced cellular breakdown and improved diffusion of soluble compounds. Consistently, the highest increase (~17.3%) was observed in DCDRT formulation (Lindsey *et al.*, 2024).

Furthermore, Rao *et al.* (2020) demonstrated that °Brix levels increased concomitantly with increased roasting levels in brews derived from Arabica coffee beans subjected to varying degrees of roasting. Consistently,

Table 1. Physicochemical properties of tahini–coffee beverages.

Sample*	Total soluble solids (°Brix)	Total acidity (100 g mL^{-1})**	pH	Color				
				L*	a*	b*	Chroma	Hue angle
MCRT	6.36 ± 0.05^{c}	4.94 ± 0.01^{a}	5.87 ± 0.06^{d}	51.44 ± 0.69^{b}	4.77 ± 0.16^{a}	20.43 ± 0.34^{a}	20.98 ± 0.37^{a}	76.85 ± 0.27^{b}
MCDRT	7.16 ± 0.05^{b}	4.80 ± 0.01^{b}	6.01 ± 0.03^{c}	45.49 ± 0.31^{c}	4.22 ± 0.10^{b}	19.60 ± 0.13^{b}	20.05 ± 0.13^{b}	77.84 ± 0.33^{a}
DCRT	7.26 ± 0.07^{b}	4.64 ± 0.01^{c}	6.27 ± 0.02^{b}	53.28 ± 0.43^{a}	4.03 ± 0.18^{b,c}	18.79 ± 0.41^{c}	19.22 ± 0.43^{c}	77.89 ± 0.41^{a}
DCDRT	7.46 ± 0.06^{a}	4.50 ± 0.01^{d}	6.50 ± 0.05^{a}	46.57 ± 0.92^{c}	3.89 ± 0.08^{c}	18.43 ± 0.32^{c}	18.84 ± 0.32^{c}	78.07 ± 0.30^{a}

Notes: Values followed by different lowercase superscript alphabets within the same column are significantly different ($P < 0.05$).
*Different combinations of roasted coffee extract (medium and dark) and tahini (roasted and double-roasted) were used in beverage samples.
**Citric acid.
MCRT: medium-roasted coffee extract + roasted tahini; MCDRT: medium-roasted coffee extract + double-roasted tahini; DCRT: dark-roasted coffee extract + roasted tahini; DCDRT: dark-roasted coffee extract + double-roasted tahini.

in the case of double-roasted tahini, microstructural degradation and the subsequent liberation of lipids and other constituents probably facilitated the transfer of soluble substances into aqueous phase. This mechanism was supported by the findings of Rababah *et al.* (2017), who observed increase in total soluble solids from 96.6 ± 0.17 in raw sesame seeds to 98.7 ± 0.11 following the roasting of sesame seeds and tahini. These results aligned with the observed increase in total soluble solids in beverage samples prepared with double-roasted tahini in our study.

Increase in °Brix values with roasting intensity cannot be attributed solely to structural changes in coffee, as the beverage represents a composite matrix consisting of both coffee and tahini. While roasting-induced cellular breakdown in coffee may enhance the release of soluble compounds, the presence of tahini introduces additional factors influencing total soluble solids.

Tahini is a lipid- and protein-rich matrix, and these components can significantly affect extraction behavior, solubility, and dispersion of soluble solids in the beverage. Lipids may limit the diffusion of certain hydrophilic compounds, whereas proteins and degraded sesame solids may contribute to the overall soluble fraction. Therefore, the observed °Brix values potentially resulted from the combined effects of coffee-derived solubles and tahini matrix interactions.

In this context, direct comparisons with coffee-only systems should be interpreted with caution, as the presence of tahini modifies extraction dynamics and physicochemical behavior of the beverage system.

Significant differences were observed in TA and pH values of the formulations. Accordingly, the MCRT sample showed the highest TA value of 4.94 g/100 mL, which represented an increase of about 8.9%, compared to the DCDRT formulation, which recorded the lowest TA value (4.50 g/100 mL). In contrast, the DCDRT formulation showed the highest pH value (6.50), while the MCRT sample exhibited the lowest pH value (5.87).

Throughout the roasting process, the chemical composition of coffee beans had significant alterations attributable to various thermal reactions, including the hydrolysis of organic acids and the synthesis of novel acidic and neutral compounds. Extended roasting at higher temperatures promoted acid degradation, resulting in lower overall acidity. Accordingly, formulations with medium-roasted coffee exhibited higher acidity and lower pH values (Bicho *et al.*, 2012; Rao *et al.*, 2020).

In a study conducted by Rune *et al.* (2023), acid concentrations were determined in samples with light-, medium-, and dark-roasting levels using different coffee varieties brewed with a French press. With increase in roasting level, a respective decrease in the average total acid concentration was observed, with values of 3.404 ± 0.240, 3.007 ± 0.223, and 2.660 ± 0.204 g/L. In parallel, pH measurements of the coffee samples showed that lighter roasted coffees had higher acidity (light: pH 3.97 ± 0.1, medium: pH 4.10 ± 0.2, and dark: pH 4.25 ± 0.1 roasting levels).

A relatively high pH values observed in the present study, compared to conventional coffee beverages, is attributed to the buffering capacity of tahini components. Tahini is rich in proteins and minerals such as calcium and magnesium, which can act as buffering agents and resist changes in pH. In addition, lipid–protein interactions within the matrix may further influence the distribution and dissociation of organic acids. Therefore, both pH and TA values of tahini–coffee beverages should not be directly compared to those of coffee-only systems, as the composite matrix significantly alters acid–base equilibria. The relatively high TA values may also reflect differences in expression units and acid equivalents, emphasizing the importance of clearly defining analytical conditions (Mennah-Govela *et al.*, 2020).

Some physicochemical properties and color features of the tahini–coffee beverages were shown in Table 1.

The L* value, which represents brightness, ranged between 45.49 and 53.28. The dark-roasted coffee extract + roasted tahini (DCRT) formulation showed the highest L* value (53.28), while both medium-roasted coffee extract + double-roasted tahini (MCDRT) and DCDRT samples showed the lowest L* values. This could be attributed to the formation of melanoidin-like pigments because of the Maillard reaction and caramelization processes that occurred during tahini roasting. The unexpected behavior of certain dark-roast combinations could be attributed to differences in melanoidin extractability and matrix interactions, as the color of the final beverage was not solely dependent on bean roasting but also on extraction dynamics and composition of the beverage system (El Hanafi *et al.*, 2023).

In a study conducted by Sdiq *et al.* (2025), sensory evaluation was performed on tahini produced from sesame seeds roasted to different degrees. The findings showed that the darkest coloration was associated with tahini obtained from seeds subjected to intense roasting, while the lightest coloration and highest consumer preferences were observed in tahini obtained from seeds subjected to light roasting.

Other color parameters, viz. a* (indicating redness) and b* (indicating yellowness), were consistently positive

in all samples, confirming the characteristic brownish-red hue of coffee–tahini beverages. Notably, a gradual decrease in both a* and b* values was observed for both MCRT to DCDRT, indicating a decrease in color intensity because of increased roasting intensity. Higher a* and b* values observed in MCRT samples indicated a warmer, reddish-yellow hue, while DCDRT samples exhibited a paler, neutral brown hue. This change could be attributed to pigment degradation and the predominance of high molecular weight melanoidins formed during advanced roasting stages (Nunes *et al.*, 2012). For example, in a study done by Yeager *et al.* (2022), different coffee extracts were obtained by brewing coffees roasted at 22°C and 92°C. Both a* and b* values of these extracts were as follows; medium a*: 23.57, medium b*: 12.44; and dark a*: 17.77, dark b*: 7.28. These results were consistent with both a* and b* values obtained in the current study, and decreased with increase in roasting.

Chroma (C*) values obtained in different formulations showed statistically significant differences in color saturation ($P < 0.05$). The MCRT sample showed the highest chroma value of 20.98, indicating that MCRT produced a beverage with more vibrant and saturated colors. Conversely, formulations containing darker roasted ingredients, especially DCRT (19.22) and DCDRT (18.84) showed decreased chroma values indicating a transition to a matte, darker, and less saturated appearance. The existing literature suggests that increasing roasting time and temperature (e.g. exposure at 220°C for up to 10 min) is associated with increased chroma values of coffee beans, leading to color differences that are perceptible to consumers (Canturk *et al.*, 2024; Otsogile *et al.*, 2022). These color changes are specifically attributed to the formation of melanoidins through the Maillard reaction (Cortés-Macías *et al.*, 2022). The observed decrease in C* values with increasing roasting intensity contrasts with some studies reporting higher chroma values at moderate roasting levels. This discrepancy could be explained by differences in roasting severity and matrix composition. While moderate roasting can enhance color vividness because of the formation of intermediate Maillard reaction products, more intense roasting promotes the formation of high molecular weight melanoidins, which contribute to darker and less saturated color tones.

In addition, the composite structure of the tahini–coffee beverage may further influence color expression. The presence of lipids and proteins from tahini can affect light scattering and pigment distribution, potentially leading to a reduction in perceived color saturation. Therefore, decrease in C* observed in this study is potentially because of both advanced roasting reactions and matrix interactions rather than a contradiction of the literature.

Notably, the hue angle values observed in this study remained relatively constant, within the range of approximately 76–78°, suggesting that roasting primarily affects chroma (C*) and lightness (L*) without altering the hue direction. This observation aligned with the findings by Bicho *et al.* (2012), who reported that roasting predominantly impacts color saturation and visual intensity rather than hue orientation.

Total proteins, lipids, and sugar analysis

Results of total proteins, lipids, and sugar analysis of tahini–coffee beverages are shown in Table 2. The protein content of the tahini–coffee beverages exhibited significant variation depending on the roasting degree of the coffee and tahini used ($P < 0.05$). Among the four formulations, the DCRT sample demonstrated the highest protein content (2.08 ± 0.02%), while DCDRT beverage had the lowest protein value (1.43 ± 0.01%). These results suggest that the level of tahini roasting affected the protein composition of the final beverage.

Protein levels observed in the present study are consistent with the literature on tahini composition. In developed tahini–coffee beverage formulations, tahini was the primary source of protein. Based on the formulation, tahini accounted for approximately 6.75% (w/w) of the beverage composition, which agreed with the protein content

Table 2. Proteins, lipids, and sugars content of tahini–coffee beverages.

Samples*	Proteins (%)	Total lipids (%)	Total sugars (%)
MCRT	1.71 ± 0.01^{b}	2.37 ± 0.04^{d}	3.74 ± 0.01^{d}
MCDRT	1.44 ± 0.00^{c}	2.75 ± 0.04^{b}	5.73 ± 0.01^{c}
DCRT	2.08 ± 0.02^{a}	2.47 ± 0.05^{c}	6.26 ± 0.01^{b}
DCDRT	1.43 ± 0.01^{c}	3.05 ± 0.05^{a}	6.84 ± 0.02^{a}

Notes: Values followed by different lowercase superscript alphabets within the same column are significantly different ($P < 0.05$).
*Different combinations of roasted coffee extract (medium- and dark-roasted) and tahini (roasted and double-roasted) were used in beverage samples.
MCRT: Medium-roasted coffee extract + roasted tahini, MCDRT: Medium-roasted coffee extract + double-roasted tahini, DCRT: Dark-roasted coffee extract + roasted tahini, DCDRT: Dark-roasted coffee extract + double-roasted tahini.

expected from tahini contribution alone. According to the United States Department of Agriculture (USDA) Food Composition Databases, tahini contains approximately 17 g protein/100 g beverage. Therefore, when 6.75 g of tahini is incorporated into 100 g of beverage, the theoretical protein contribution would be around 1.14%, which aligns well with the experimentally determined values in this study.

However, variations in protein content of tahini have been reported depending on production methods. For instance, Borchani *et al.* (2010) found that raw sesame seeds contained approximately 24% protein, which slightly decreased in tahini because of processing. Similarly, previous studies on tahini from various sources reported protein contents ranging from 16.08% to 24.7%, depending on the factors such as seed variety, dehulling, and roasting conditions (Hou *et al.*, 2018).

Our findings also revealed that double-roasting tahini resulted in a 15% decrease in protein content (from MCRT to MCDRT) among the samples prepared with medium-roasted coffee extracts, and a 31.25% decrease (from DCRT to DCDRT) among the samples prepared with dark-roasted coffee extracts. This pronounced decline in protein levels in beverages containing double-roasted tahini, compared to those formulated with roasted tahini, suggested that prolonged heat exposure could induce protein degradation. Previous research indicated that thermal processing could disrupt the structural integrity of proteins, consequently impairing their extractability (Zhang *et al.*, 2024).

Overall, these findings highlight the impact of selection of raw material and processing conditions on the protein composition of tahini–coffee beverages. Unlike many almond- or rice-based beverages, which are generally low in protein, tahini-containing formulations may offer a more nutrient-dense matrix because of natural protein and unsaturated lipids content of sesame. Further research focusing on changes in protein structure during roasting and extraction could provide more detailed information about the optimization of the nutritional profile of such beverage formulations.

Among the samples, DCDRT had the highest total lipid content (3.05 ± 0.05%), while MCRT had the lowest lipid values (2.37 ± 0.04%; Table 2). These differences suggest that the roasting degree of tahini plays a crucial role in the composition of lipids of the final beverage, with double-roasting leading to increased oil extraction (Durmaz and Gökmen, 2010).

A study examined the lipids content and composition of different coffee types prepared from roasted *C. arabica* and *C. robusta* beans. The brewing method significantly affected the lipids content; less than 7 mg lipids were found in paper-filtered coffees and 60–160 mg lipids/150 mL cup in espresso and decoction coffee types. In all samples, triglycerides and diterpene alcohol esters were the main lipid classes, accounting for about 97% and 3% in instant coffee, respectively. The findings indicate that the total amount of lipids in coffee varies depending on processing conditions (Rahn and Yeretzian, 2019).

The results are consistent with the literature, which reports that lipids are one of the important components of tahini and that the lipids content varies between 51.80% and 61.56% depending on the sesame variety and processing conditions. Studies showed that the crude oil content in tahini varied between 58.6% and 59.4% (El-Adawy and Mansour, 2000). These variations are influenced by multiple factors, including dehulling process and roasting conditions. The observed increase in lipids content in beverages containing double-roasted tahini (MCDRT and DCDRT) could be attributed to the enhanced breakdown of cell structures during intense roasting, which facilitates release of oil (Arab *et al.*, 2022).

In addition to tahini composition, the coffee brewing process also plays a significant role in the extraction of lipids. Previous studies indicate that several factors, such as roasting degree, particle size, extraction time, pressure, and coffee-to-water ratio, influence the chemical composition of the final brew (Maksimowski *et al.*, 2022).

Overall, the findings highlight the combined effects of selection of ingredients and processing conditions on the extraction of lipids in tahini–coffee beverages. The results indicate that both roasting degree of tahini and coffee influence the final lipids content, with DCDRT yielding the highest lipid levels.

In our study, the total sugar content in the developed tahini coffee beverages showed significant differences depending on the processing conditions of both coffee and tahini. The lowest total sugar value (3.74%) was measured in the MCRT sample, while the highest value (6.84%) was discovered in the DCDRT sample. Therefore, it was determined that DCDRT had the highest sugar content.

Although apple juice concentrate was used at identical proportions (9.85%, w/v), differences observed in total sugars content were potentially associated with the interaction between roasting intensity and the tahini–coffee matrix. Roasting processes promote complex reactions, including the Maillard reaction and caramelization, in

which reducing sugars react with amino compounds, while the thermal degradation of polysaccharides may simultaneously generate low molecular weight sugars. However, these processes occur concurrently with consumption of sugars in Maillard reactions, resulting in a dynamic balance, rather than a simple increase in sugars content (He *et al.*, 2025).

Furthermore, sesame-based matrices contain proteins, lipids, and carbohydrates that undergo thermal and structural modifications during roasting, influencing the release of soluble compounds. These changes affect the extractability and measurable concentration of sugars rather than their absolute formation (Jin *et al.*, 2022).

In addition, interactions between sugars, proteins, and lipids within the tahini–coffee system may alter sugar solubility and analytical recovery. Therefore, the observed variations in sugar content potentially reflect combined matrix effects, roasting-induced transformations, and extraction behavior rather than the contribution of apple juice concentrate alone (Pucci *et al.*, 2024).

However, the sugar levels observed in all samples are reasonable when compared to similar commercial beverages. For example, while cow's milk naturally contains approximately 5% lactose, it has been reported that most plant-based milk products contain higher total sugar levels along with added sugar. Walther *et al.* (2022) noted in their study that seven out of 10 different plant-based beverages contained higher sugar levels than cow's milk and that sugar content increased in heat-treated plant beverages. A 200-mL bottle of our tahini coffee beverage contains approximately 7.5–13.7 g of sugar.

This amount corresponds to 15–28% of the maximum daily content of sugar limit recommended by the World Health Organization (WHO, 2015) (10% energy, 50 g/day). The WHO (2015) recommends lowering this limit to 5% of energy intake (25 g/day) for additional health benefits; in this case, a single serving (200 mL) of our tahini–coffee beverage corresponds to at most half of this stricter limit. Therefore, our tahini–coffee beverage provides a reasonable level of sweetness while containing sugar within the limits that can be consumed daily.

Total caloric value

Total caloric value of tahini–coffee beverages is shown in Table 3. The lowest energy value was observed in the MCRT sample, while the highest value was found in the DCDRT sample (Table 3). These differences could be due to slightly higher lipids and sugars content present, particularly in the formulations containing double-roasted tahini. Tahini is a high-calorie ingredient containing approximately 50% lipids and 20% proteins in its composition; therefore, an increase in tahini ratio or a change in surface activity and distribution of lipids because of the double-roasting process may have slightly increased the calorie level of the beverage (Ali *et al.*, 2022; Mostashari and Mousavi Khaneghah, 2024).

Table 3. Total calorie value of tahini–coffee beverages.

Sample*	Total calorie value (kcal)
MCRT	43.13 ± 0.36^{d}
MCDRT	53.43 ± 0.40^{c}
DCRT	55.59 ± 0.57^{b}
DCDRT	60.54 ± 0.55^{a}

Notes: Values followed by different lowercase superscript alphabets within the same column are significantly different ($P < 0.05$).
*Different combinations of roasted coffee extract (medium and dark) and tahini (roasted and double-roasted) were used in beverage samples.
MCRT: medium-roasted coffee extract + roasted tahini; MCDRT: medium-roasted coffee extract + double-roasted tahini; DCRT: dark-roasted coffee extract + roasted tahini; DCDRT: dark-roasted coffee extract + double-roasted tahini.

The energy values presented in Table 3 are expressed per 100 mL of beverage. Accordingly, a 200-mL serving provides approximately 86–121 kcal, depending on the formulation. This value is significantly lower than that of latte- or sweet-flavored coffee extracts prepared with whole milk in a similar serving size. For example, a large ginger latte can have a very high energy content of approximately 523 kcal (Gallagher, 2019). In comparison, the calories content of our beverage samples is not at a level that could replace a meal, but rather at a level that could be considered a snack.

When evaluating the contribution of energy content to daily nutrition, a 200-mL serving of our beverage provides only about 5–6% of the daily calorie requirement based on a 2,000 kcal reference diet. According to nutrition labeling criteria, a serving that provides <5% of the daily value is considered low. Therefore, our product's energy contribution is low and does not impose an excessive burden on diet. Our beverage's contribution to daily intake is also limited in terms of nutrients. Looking at the formulation, it can be calculated that one serving (200 mL) contains approximately 4.74–6.1 g of lipids and 2.86–4.16 g of proteins; this corresponds to approximately 6.08–7.82% of the total lipid requirement of 78 g and only 5.72–8.32% of the recommended daily protein intake of 50 g (US Food and Drug Administration [US FDA], 2023).

In terms of added sugars, one serving of our 200 mL contains approximately 7.5–13.7 g of limit, which accounts for no more than a quarter of the maximum recommended sugar intake (10% of energy) in a 2,000-kcal diet (WHO, 2015). These analyses show that the tahini–coffee beverage developed in this study does not lead to excessive consumption in daily nutrition in terms of its nutritional value but provides a certain amount of energy and macronutrient support. This product adds variety to diets of individuals who consume plant-based beverages, and with its reasonable calorie and nutrient content, it can be consumed as a snack or breakfast supplement. In conclusion, our tahini–coffee beverage offers a balanced calorie profile and a composition consistent with daily recommended intake values. Hence, our product can be considered a healthy alternative that can compete with similar functional beverages.

Caffeine analysis with HPLC

The caffeine content of tahini–coffee beverages is shown in Table 4. Caffeine levels in the beverages were found to be statistically different. The highest caffeine content was measured in the DCRT sample (372.5 mg/L), followed by MCDRT (342.9 mg/L) and MCRT (328.1 mg/L). The DCDRT sample had the lowest caffeine level (321.9 mg/L) (Table 4).

In beverages prepared with dark-roasted coffee, the degree of tahini roasting could have affected caffeine extraction; for example, the use of double-roasted tahini appears to have slightly reduced caffeine in dark coffee extract (DCDRT < DCRT), while it slightly increased the caffeine content in medium-roasted coffee extracts (MCDRT > MCRT). The concept of food matrix effect emphasizes the role of components such as lipids and proteins and the structural properties of the matrix on solubility and extraction (Aguilera, 2019). This is attributed to the effect of the components of tahini matrix on the solubility and stability of caffeine.

Table 4. Caffeine content of tahini–coffee beverages.

Sample*	Caffeine (mg/L)
MCRT	328.05 ± 0.04[c]
MCDRT	342.93 ± 0.02[b]
DCRT	372.53 ± 0.06[a]
DCDRT	321.86 ± 0.01[d]

Notes: Values followed by different lowercase superscript alphabets within the same column are significantly different ($P < 0.05$).
*Different combinations of roasted coffee extract (medium and dark) and tahini (roasted and double-roasted) were used in beverage samples.
MCRT: medium-roasted coffee extract + roasted tahini; MCDRT: medium-roasted coffee extract + double-roasted tahini; DCRT: dark-roasted coffee extract + roasted tahini; DCDRT: dark-roasted coffee extract + double-roasted tahini.

On the other hand, all formulations provide a functionally meaningful dose of caffeine. A 200-mL serving of the beverage provides approximately 64–75 mg of caffeine, which is lower than typically brewed coffee but still represents a moderate caffeine level within commonly reported intake extents. This value is close to the caffeine content of a 220-mL cup of brewed tea (50 mg) and slightly lower than that of a standard filtered coffee of similar volume (90 mg/200 mL) (European Food Safety Authority [EFSA] Panel on Dietetic Products, Nutrition, and Allergies [NDA], 2015). Therefore, our tahini–coffee beverage provides a moderate caffeine load, although lower than a traditional cup of brewed coffee. This amount of caffeine is well below the established safe intake limits for healthy adults: according to the EFSA (2015) data, a daily intake of 400 mg of caffeine and a single intake of up to 200 mg are generally considered safe for healthy adults. In this context, a 200-mL bottle of our beverage contains approximately 16–19% of the daily safe caffeine limit and approximately 35% of the single-dose safe limit, at which levels no adverse effects are expected. Furthermore, according to the EFSA (2015) panel assessments, a single intake of at least 75 mg of caffeine can provide a noticeable improvement in mental alertness and attention (Wierzejska and Gielecińska, 2024). In our study, 200 mL serving approaches this threshold, offering consumers a mild-to-moderate stimulating effect.

Total phenolic content, total antioxidant capacity (DPPH, FRAP, and CUPRAC methods), and their *in vitro* bioaccessibility

Total phenolic content

In undigested state, TPC ranged from 2194.61 ± 1.65 mg GAE/100 g to 562.29 ± 4.96 mg GAE/100 g, with the MCRT sample exhibiting the highest TPC, followed by MCDRT ($P < 0.05$) (Table 5).

Bioaccessible phenolics were determined between 3446.62 ± 12.86 mg GAE/100 mL and 4042.08 ± 71.26 mg GAE/100 mL. In their study, Nosal *et al.* (2022) reported that the phenolic content of brewed coffee extract samples ranged approximately from 1,240 mg GAE/L to 1,934 mg GAE/L.

The findings demonstrated that the degree of roasting significantly affected the TPC of samples. Specifically, the DCDRT formulation exhibited the lowest TPC value, implying that the concurrent application of higher roasting intensities to both coffee and tahini

Table 5. Results of total phenolic content (TPC) and their *in vitro* bioaccessibility.

Analysis	Undigested	After *in vitro* digestion process	
		Gastric digested	Intestinal digested
TPC (mg GAE/100 g DM)			
MCRT*	2,562.29 ± 4.96^{a,b}	1,129.88 ± 4.96^{a,C}	2,934.75 ± 9.03^{b,A}
MCDRT	2,533.02 ± 9.93^{b,B}	1,091.94 ± 8.94^{b,C}	3,147.82 ± 5.07^{a,A}
DCRT	2,242.62 ± 6.62^{c,B}	949.32 ± 5.96^{c,C}	2,562.49 ± 5.07^{d,A}
DCDRT	2,194.61 ± 1.65^{d,B}	933.16 ± 4.96^{d,C}	2,630.72 ± 5.07^{c,A}

Notes: There is a significant difference between values shown in different lowercase superscript alphabets within the same column and different uppercase superscript alphabets within the same row ($P < 0.05$).
*Different combinations of roasted coffee extract (medium and dark) and tahini (roasted and double-roasted) were used in beverage samples.
MCRT: medium-roasted coffee extract + roasted tahini; MCDRT: medium-roasted coffee extract + double-roasted tahini; DCRT: dark-roasted coffee extract + roasted tahini; DCDRT: dark-roasted coffee extract + double-roasted tahini.

could facilitate the degradation of phenolic compounds. In coffee, the major phenolic fraction may undergo thermal degradation at elevated temperatures, leading to structural breakdown, oxidative reactions, or transformation into lower molecular weight compounds, thereby resulting in reduced measurable TPC with increase in roasting intensity (Wu *et al.*, 2022a).

Roasting influences phenolic composition through two concurrent mechanisms. Moderate thermal treatment promotes the release of phenolics previously associated with cellular matrix, increasing extractability, whereas excessive roasting induces degradation, oxidation, polymerization, or incorporation of phenolics into the Maillard reaction-derived melanoidin structures. Consequently, the final bioaccessible fraction depends on the balance between phenolic liberation and thermal loss. In coffee systems, hydroxycinnamic acids, such as chlorogenic acid derivatives, are particularly sensitive to roasting intensity, while newly formed Maillard reaction products can contribute to antioxidant responses after digestion (Wu *et al.*, 2022b).

Compared to the MCRT sample, the DCRT sample—characterized by a more intensely roasted coffee—showed a 12.47% decrease in TPC. Similarly, the MCDRT sample, which contained more heavily roasted tahini relative to the MCRT sample, exhibited a marginal reduction of 1.14% in TPC. This is attributed to the relatively higher thermal stability of sesame-derived phenolic acids and lignans, compared to those in coffee. Overall, an increase in roasting intensity was associated with an approximately 14.3% decline in TPC, which can be explained by the thermal degradation and structural transformation of phenolic acids as well as their potential interactions with high-molecular-weight melanoidins formed during Maillard reaction, leading to a reduction in the phenolic fraction detectable by the Folin–Ciocalteu assay (Dybkowska *et al.*, 2017).

This observation aligned with prior research indicating that the content of phenolic compounds in *C. arabica* beans diminishes with progress in roasting intensity from light to dark levels (Wu *et al.*, 2022a). However, it is also reported that partially bound phenolic compounds present in the plant matrix are released during thermal processing because of the degradation of cellulose and other cell wall components, potentially increasing the extractable phenolic fraction at moderate processing conditions (Mehari *et al.*, 2021).

Similarly, Król *et al.* (2020) in their study observed a decrease in TPC with roasting intensity of coffee beans.

In a comparative study, filtered coffee extracts (11–12.5% w/v concentration of coffee) prepared from differently roasted beans—Ethiopia Uraga (light roast), Gardelli Specialty's washed Kenya Thiriku (medium-roasted), and Starbucks Blonde 100% Arabica (dark roast)—exhibited the TPC values of 208, 228, and 285 mg GAE/100 g, respectively (Santanatoglia *et al.*, 2023). Compared to the TPC values observed in other beverages, it appears that our beverage has a high TPC. This can be explained by the tahini used with the coffee extract.

Given that the beverage formulation incorporates both coffee and tahini, the relatively elevated TPC values cannot be solely attributed to coffee phenolics. This highlights the significant contribution of tahini as an additional source of phenolic compounds in the overall composition.

Results of a study conducted by Sadeghi *et al.* (2020) demonstrated considerable variation in the TPC of tahini

samples sourced from diverse regions across Iran, with values ranging from 251.49 μmol GAE/mL to 2057.33 μmol GAE/mL. These results suggest that factors, such as geographical origin and processing conditions, play a significant role in determining the phenolic profile of tahini.

Similar phenomena are observed in the context of sesame roasting, where Jannat *et al.* (2013) reported that elevated temperatures and extended roasting duration could result in a reduction of certain phenolic compounds.

A noticeable decrease in TPC (55.9–57.66%) was observed during gastric digestion stage, whereas an increase at intestinal pH conditions (14.53–24.27%) was found, compared to the undigested samples. This indicates that phenolic compounds may undergo partial degradation in acidic gastric environment but can be released or transformed into more soluble forms of intestinal conditions with higher pH. This trend is particularly evident in the MCRT and MCDRT samples, where TPC values increased beyond their initial levels during the intestinal phase, suggesting enhanced release and solubility of phenolic compounds. The acidic environment and enzymatic action during gastric digestion potentially contributed to the breakdown or transformation of certain phenolic compounds, reducing their detectable levels (Wojtunik-Kulesza *et al.*, 2020). Similar trends were also reported in previous studies, which demonstrated a reduced phenolic stability in gastric phase, followed by a significant increase in TPC after intestinal digestion, attributed to the hydrolysis of bound phenolics and their enhanced release from food matrix under intestinal pH conditions (Suna and Erdal, 2025).

Total phenolic content increased significantly during *in vitro* intestinal digestion, with MCDRT exhibiting the highest TPC (3147.82 ± 5.07 mg GAE/100 g). This suggests that specific phenolic compounds were released or transformed into more bioaccessible forms under alkaline intestinal conditions (Rodríguez-Roque *et al.*, 2013).

Overall, the findings highlight that medium-roasted coffee combined with roasted or double-roasted tahini retained the highest phenolic content across all digestion phases, particularly in the intestinal phase, where phenolic bioaccessibility was maximized.

Total antioxidant capacity (DPPH, FRAP, and CUPRAC methods)

Antioxidant capacity was analyzed using three different methods: DPPH, FRAP, and CUPRAC. Results of the analysis are presented in Table 6. The results are expressed on a DM basis, which allows a more accurate

Table 6. Results of total antioxidant capacity analysis and their *in vitro* bioaccessibility.

TAC (μmol TE/g DM)			
DPPH (μmol TE/g DM)			
MCRT	133.52 ± 1.21^{c,B}	50.92 ± 1.04^{b,C}	289.06 ± 1.21^{a,A}
MCDRT	131.48 ± 0.01^{d,B}	60.43 ± 2.01^{a,C}	281.40 ± 0.80^{b,A}
DCRT	153.03 ± 0.91^{b,A}	31.57 ± 0.31^{d,C}	89.96 ± 2.82^{d,B}
DCDRT	167.75 ± 3.71^{a,B}	46.79 ± 0.11^{c,C}	194.34 ± 0.80^{c,A}
CUPRAC (μmol TE/g DM)			
MCRT	67.85 ± 0.11^{a,C}	121.61 ± 1.84^{a,B}	479.88 ± 1.23^{a,A}
MCDRT	65.65 ± 0.11^{b,C}	121.00 ± 1.29^{a,B}	285.30 ± 0.82^{b,A}
DCRT	67.19 ± 0.22^{a,C}	119.40 ± 2.28^{a,B}	160.09 ± 0.49^{d,A}
DCDRT	67.54 ± 1.34^{a,C}	114.30 ± 1.29^{b,B}	218.79 ± 0.01^{c,A}
FRAP (μmol TE/g DM)			
MCRT	34.51 ± 1.30^{a,C}	155.51 ± 1.34^{b,B}	385.02 ± 5.84^{b,A}
MCDRT	35.36 ± 1.07^{a,C}	193.47 ± 0.94^{a,B}	411.04 ± 2.06^{a,A}
DCRT	30.92 ± 1.97^{b,C}	128.49 ± 0.26^{c,B}	313.79 ± 4.12^{d,A}
DCDRT	34.47 ± 1.25^{a,C}	154.94 ± 3.22^{b,B}	368.49 ± 1.03^{c,A}

Notes: There is a significant difference between values shown in different lowercase superscript alphabets within the same column and different uppercase superscript alphabets within the same row ($P < 0.05$).
*Different combinations of roasted coffee extract (medium and dark) and tahini (roasted and double-roasted) were used in beverage samples.
MCRT: medium-roasted coffee extract + roasted tahini; MCDRT: medium-roasted coffee extract + double-roasted tahini; DCRT: dark-roasted coffee extract + roasted tahini; DCDRT: dark-roasted coffee extract + double-roasted tahini.

comparison of bioactive compound levels by excluding variations in moisture content.

Differences observed between DPPH, FRAP, and CUPRAC results can be attributed to the distinct antioxidant mechanisms measured by each assay. While DPPH reflects radical scavenging activity, FRAP and CUPRAC evaluate reducing power through electron transfer reactions. Therefore, certain compounds, such as the Maillard reaction products or specific phenolic structures, may exhibit strong radical scavenging capacity but relatively lower reducing power. This may explain why the DCDRT sample showed the highest DPPH value but not the highest FRAP and CUPRAC values. Such discrepancies are widely reported in the literature, emphasizing that antioxidant capacity is method-dependent and influenced by the chemical nature of the compounds present (Shah and Modi, 2015).

The antioxidant activity of the developed tahini–coffee beverages, as measured by the DPPH radical scavenging assay, exhibited significant variations depending on the roasting degree of both coffee and tahini as well as the digestion phase ($P < 0.05$) (Table 6). Undigested samples showed the highest antioxidant activity in DCDRT (167.75 ± 3.71 μmol TE/g DM), followed by DCRT (153.03 ± 0.91 μmol TE/g DM) (Table 6). In a study conducted by Santanatoglia *et al.* (2023), filtered coffee was obtained using three different coffee varieties (Ethiopia Uraga for a light roast, Gardelli Specialty's washed Kenya Thiriku for a medium roast, and roasted Starbucks Blond 100% Arabica for a dark roast). The respective DPPH values in these samples were determined as light: 5265.57 ± 42.35 mg TE/L, medium: 4369.99 mg TE/L, and dark: 5232.16 mg TE/L.

In Santanatoglia *et al.* (2023), differences in DPPH radical scavenging activity among roasting degrees were also found to be statistically significant, supporting the influence of roasting level on antioxidant capacity.

Samples containing dark-roasted coffee (DCRT and DCDRT) exhibited greater DPPH values compared to those prepared with medium-roasted coffee (MCRT and MCDRT), suggesting that a higher degree of roasting contributes to the formation of the Maillard reaction products and melanoidins, which are known for their antioxidant properties (Vignoli *et al.*, 2011). In studies (Iriondo-DeHond *et al.*, 2021; Wołosiak *et al.*, 2023) conducted especially with coffee beans and coffee extracts, it was reported that antioxidant capacity increased with an increase in melanoidins during roasting, similar to the finding of our study.

Furthermore, elevation in the roasting levels of both coffee and double-roasted tahini was found to influence positively DPPH radical scavenging activity. During the roasting process of double-roasted tahini, the formation and release of phenolic lignans, such as sesamol and sesaminol, together with the increased production of the Maillard reaction-derived compounds, significantly contribute to the enhancement of antioxidant potential. Accordingly, the observation that the DCDRT sample exhibited the highest DPPH radical scavenging activity highlights the synergistic effect of roasting degree on antioxidant capacity (Dybkowska *et al.*, 2017; Santanatoglia *et al.*, 2023).

During *in vitro* gastric digestion, DPPH values decreased significantly in all samples, with the lowest activity observed in DCRT (31.57 ± 0.31 μmol TE/g DM) and the highest in MCDRT (60.43 ± 2.01 μmol TE/g DM). This reduction is potentially related to the acidic gastric environment and enzymatic activity, which may degrade phenolic compounds and other antioxidants (Ketnawa *et al.*, 2022).

Following intestinal digestion, DPPH values increased markedly in all samples, with MCRT showing the highest level (289.06 ± 1.21 μmol TE/g DM). This increase is attributed to the release of bound phenolic compounds and structural changes in food matrix during digestion, which enhance the accessibility of antioxidant compounds.

The increased antioxidant capacity observed during intestinal digestion can be attributed to the release of different forms of bound phenolic compounds present in food matrix. Phenolics in coffee- and sesame-based systems are known to exist not only in free form but also as esterified, glycosylated, and matrix-bound compounds. During digestion, these compounds are released through enzymatic and physicochemical processes (Tarko *et al.*, 2013).

In the gastric phase, acidic conditions and pepsin activity can initiate the breakdown of protein–phenolic interactions. In the intestinal phase, enzymes such as pancreatin, including esterases and carbohydrases (both hydrolase enzymes), can hydrolyze ester and glycosidic bonds, leading to the release of phenolic acids (e.g., hydroxycinnamic acids) and flavonoid derivatives. In addition, structural disruption of food matrix facilitates the liberation of phenolics previously bound to macromolecules, such as polysaccharides or melanoidins (Kasprzak-Drozd *et al.*, 2024).

These mechanisms collectively contribute to the increased bioaccessibility and antioxidant capacity observed after intestinal digestion, as reported in previous studies on phenolic-rich food systems (Mennah-Govela *et al.*, 2020).

However, DCRT exhibited comparatively lower antioxidant activity in the intestinal phase, suggesting that interactions between dark-roasted coffee and tahini components may limit the stability or release of antioxidant compounds under these conditions.

The tahini matrix may also modulate compound release during digestion because of its complex composition rich in lipids, proteins, and structural carbohydrates. Protein–phenolic and lipid–phenolic interactions can initially limit extractability by retaining bioactive compounds within the matrix. However, during gastrointestinal digestion, enzymatic hydrolysis of proteins and lipid emulsification may progressively weaken these interactions and facilitate compound release. In addition, the viscous and colloidal nature of tahini may alter diffusion behavior and improve the stability of oxidation-sensitive compounds throughout digestion (Luo *et al.*, 2022).

The antioxidant capacity determined by the FRAP method in undigested samples ranged from 30.92 ± 1.97 μmol TE/g DM to 35.36 ± 1.07 μmol TE/g DM (Table 5). In a study conducted by Tamer (2018), a functional beverage (10% and 15% w/v concentration of coffee) and the FRAP values of the beverage samples ranged between 729 ± 0.03 μmol trolox/100 mL and 794 ± 0.04 μmol trolox/100 mL. Sánchez-González *et al.* (2005) determined FRAP values in filtered coffee extracts having 2.5% (w/v) concentration of the coffee prepared using different Colombian coffee varieties with medium- and dark-roasting levels. The beverage prepared from medium-roasted coffee showed an FRAP value of 240 ± 4 μmol TE/g DM, while the beverage prepared from dark-roasted coffee showed an FRAP value of 221 ± 2 μmol TE/g DM. Also, in a study (Sadeghi *et al.*, 2020), FRAP method was used to measure the total antioxidant activity in each tahini sample. The results ranged from 119.93 ± 0.159 μmol/mL to 16.34 ± 0.023 μmol/mL. These differences could be due to the type of coffee and tahini and raw materials as well as different processing conditions used in the beverage.

The DCRT sample exhibited lower FRAP values compared to other samples before and after digestion. During gastric digestion, FRAP values increased by approximately 3.24–4.47 fold, compared to the undigested state, while intestinal digestion increased antioxidant capacity by 9.62–10.62 fold, indicating a significant increase in the reducing power of post-digestion samples. This marked increase in FRAP activity during the intestinal phase suggests that the digestive process may promote the release of bound antioxidant compounds or their conversion to more bioavailable forms.

During *in vitro* gastric digestion, a significant increase in antioxidant activity was observed across all samples, with MCDRT again showing the highest value (193.47 ± 0.94 μmol TE/g DM), followed by MCRT (155.51 ± 1.34 μmol TE/g DM). A substantial rise in FRAP values during gastric digestion is consistent with previous studies, indicating that acidic conditions and enzymatic activity can facilitate the release or transformation of bound polyphenols and the Maillard reaction products, enhancing their reducing power (Bouayed *et al.*, 2011; Han *et al.*, 2024).

Following *in vitro* intestinal digestion, a further increase in antioxidant activity was recorded, with MCDRT having the highest FRAP value (411.04 ± 2.06 μmol TE/g DM), while DCRT exhibiting the lowest FRAP value (313.79 ± 4.12 μmol TE/g DM). The elevated antioxidant potential in the intestinal phase suggests improved bioaccessibility of redox-active compounds, possibly because of the breakdown of food matrices and enhanced solubility of phenolic compounds (Kamiloğlu and Capanoglu, 2014).

In the undigested state, the CUPRAC values, ranging from 65.65 ± 0.11 μmol TE/g DM to 67.85 ± 0.11 μmol TE/g DM, were relatively close in all samples (Table 5). In a study (Anh-Dao *et al.*, 2022), three different coffee types (Arabica, Robusta, and Liberica) were processed at three different roasting intensities (light, medium, and dark). As a result of the study, the CUPRAC values of coffee samples ranged from 222.4 ± 2.6 μmol TE/g to 298.22 ± 0.49 μmol TE/g. In a study conducted on tahini enriched with natural plant extracts (Achilladelis *et al.*, 2023), the CUPRAC results ranged from 46.1 ± 2.1 to 81.9 ± 0.4. The CUPRAC values of both coffee and tahini are affected by different factors, especially the process conditions, as observed in the results of the analysis performed by other antioxidant capacity methods.

During *in vitro* gastric digestion, the overall increase in the CUPRAC values was observed, suggesting an enhanced release of antioxidant compounds under acidic conditions and enzymatic action. However, differences between samples were less pronounced in this phase. MCRT maintained the highest antioxidant potential (121.61 ± 1.84 μmol TE/g DM), while DCDRT exhibited the lowest value (114.30 ± 1.29 μmol TE/g DM). In addition, following *in vitro* intestinal digestion, substantial variations in antioxidant activity were detected. MCRT exhibited the highest antioxidant activity (479.88 ± 1.23 μmol TE/g DM), indicating improved bioaccessibility of antioxidant compounds in this formulation.

Overall, the results highlight dynamic changes in antioxidant activity throughout digestion, with MCRT showing the most favorable antioxidant profile. The marked increase in antioxidant activity in the intestinal phase for

MCRT suggests that specific processing conditions may enhance the stability and bioaccessibility of antioxidant compounds. Further investigations into the structural changes of phenolic compounds and their interactions with food matrices during digestion could provide valuable insights for optimizing functional coffee-based beverages with improved health benefits.

The holistic evaluation of DPPH, FRAP, and CUPRAC methods emphasizes that TAC of tahini–coffee beverages is influenced not only by the phenolic content they possess but also by the structural transformations induced by the roasting and digestive environment. A marked increase in antioxidant activity at intestinal stage, especially in formulations containing moderately roasted coffee and roasted tahini (MCRT), suggests that specific processing conditions may alter the release and biotransformation of bound phenolic compounds into more bioavailable forms. These findings are in line with previous reports, indicating that gastrointestinal conditions can promote release of the Maillard reaction products and melanoidins, which have significant redox activity and interact synergistically with phenolic antioxidants (Aljahdali and Carbonero, 2019).

However, a relatively lower antioxidant potential observed in dark coffee–roasted tahini combinations (DCRT) during digestion suggests that excessive heat processing may lead to degradation or polymerization of components with antioxidant properties. This suggests that despite their high initial radical scavenging capacity in the undigested state, their bioactivity may decrease upon *in vitro* digestion. This result was documented in complex food matrices where advanced melanoidin structures trapped phenolic compounds, limiting their release from the intestines (Wu *et al.*, 2022a).

All things considered, the results emphasize that TAC should be assessed not only at the formulation stage but also under dynamic digestion conditions, which determine the physiological importance of such beverages.

Although the *in vitro* gastrointestinal digestion model provides valuable insights into the potential bioaccessibility of phenolic compounds and antioxidant capacity, it is important to acknowledge its inherent limitations. *In vitro* models simulate certain physicochemical conditions of the human gastrointestinal tract; however, they cannot fully replicate the complexity of *in vivo* systems, including factors such as intestinal absorption, metabolism, and interactions with gut microbiota. Therefore, the results obtained in this study should be interpreted as an estimation of the potential bioaccessibility rather than actual bioavailability.

Moreover, the bioaccessibility of phenolic compounds is strongly influenced by their interactions with food matrix, digestive enzymes, and other macromolecules, such as proteins and lipids. These interactions may lead to either enhanced release or reduced availability of bioactive compounds depending on the specific matrix composition. Previous studies have demonstrated that such interactions can significantly modify phenolic stability and antioxidant activity during digestion.

Consequently, while the observed increase in antioxidant capacity during the intestinal phase suggests the potential release of bound compounds, further *in vivo* studies are required to confirm their physiological relevance and health effects.

Sensory analysis

The sensory evaluation of tahini coffee beverage samples revealed significant differences in color, odor, taste, coffee aroma, tahini aroma, bitterness, and the overall acceptability as influenced by the roasting intensity of coffee and tahini (Table 7).

Table 7. Results of sensory analysis.

Samples*	Color	Odor	Taste	Coffee aroma	Tahini aroma	Bitterness	General acceptability
MCRT	4.28 ± 0.95^{c}	4.28 ± 0.75^{b}	4.14 ± 0.69^{a}	4.00 ± 0.15^{a}	4.28 ± 0.75^{a}	4.14 ± 0.89^{a}	3.71 ± 0.75^{c}
MCDRT	4.57 ± 0.53^{b}	4.14 ± 0.69^{c}	4.00 ± 0.57^{b}	3.57 ± 0.97^{c}	3.57 ± 0.97^{c}	3.57 ± 0.97^{c}	4.14 ± 0.37^{b}
DCRT	4.14 ± 0.89^{d}	4.14 ± 0.69^{c}	4.14 ± 0.89^{a}	3.85 ± 0.21^{b}	4.00 ± 0.81^{b}	4.00 ± 0.98^{b}	4.28 ± 0.75^{a}
DCDRT	4.71 ± 0.48^{a}	4.42 ± 0.78^{a}	3.57 ± 0.78^{c}	3.57 ± 0.78^{c}	3.57 ± 0.97^{c}	3.42 ± 0.97^{d}	3.71 ± 0.75^{c}

Notes: Values followed by different lowercase superscript alphabets within the same column are significantly different ($P < 0.05$).
*Different combinations of roasted coffee extract (medium and dark) and tahini (roasted and double-roasted) were used in beverage samples.
MCRT: medium-roasted coffee extract + roasted tahini; MCDRT: medium-roasted coffee extract + double-roasted tahini; DCRT: dark-roasted coffee extract + roasted tahini; DCDRT: dark-roasted coffee extract + double-roasted tahini.

Color scores were relatively high in all samples, with DCDRT scoring the highest, while DCRT scored the lowest mark. In terms of aroma, MCRT exhibited the most prominent coffee–tahini notes, indicating that a moderate roasting level preserved characteristic flavors (Figure 2). According to bitterness assessment, MCRT was the most appreciated product, followed by DCRT. The DCDRT sample scored lowest in the bitterness parameter.

Evaluation of the general acceptability parameter showed that DCRT emerged as the most preferred formulation. This formulation offered a balanced flavor, thanks to the moderate roasting of tahini, while the dark-roasted coffee was effective in balancing the taste. On the other hand, DCDRT, despite its high color and odor assessments, scored lowest in terms of general acceptability, indicating that over-roasting negatively affected sensory harmony of the product. These findings highlight the critical role of roasting levels in shaping sensory attributes and reveal that an optimal balance between roasting intensity and ingredient composition is necessary to maximize consumer preference.

Our findings are consistent with the literature. For example, Hu *et al.* (2020) systematically demonstrated the effect of roasting intensity and duration on sensory characteristics and reported that dark-roasted samples were perceived as more bitter, and less acidic and sweet. In another study (Liang *et al.*, 2024), the effect of parameters, such as brewing time, brewing temperature, and roasting density on sensory properties, was investigated and it was reported that the most effective factor on sensory results among these parameters was roasting density.

Correlation analysis in tahini–coffee beverages

In this study, relationships between TAC values (DPPH, FRAP, and CUPRAC), TPC values, and their *in vitro* bioaccessibility values (DPPH [gastric], DPPH [intestinal], FRAP [gastric], FRAP [intestinal], CUPRAC [gastric], CUPRAC [intestinal], TPC [gastric], and TAC [intestinal]), protein and lipids content, and sensory properties (color, odor, taste, coffee aroma, tahini aroma, bitterness, and general acceptability) of the samples were analyzed using correlation coefficients. As presented in Figure 3, both positive and negative significant correlations were observed among the evaluated parameters.

A very strong positive correlation was observed between the results of DPPH analysis performed in the gastric phase and FRAP analysis performed in the intestinal phase of the beverage samples (R^2 = 1.00). Similarly, the TPC values obtained in the pre-digestion phase and post-digestion gastric and intestinal phases of the beverages exhibited a strong positive correlation with R^2 = 0.99 and R^2 = 0.90, respectively. The results of DPPH analysis performed before digestion were negatively correlated with other antioxidant analyses and

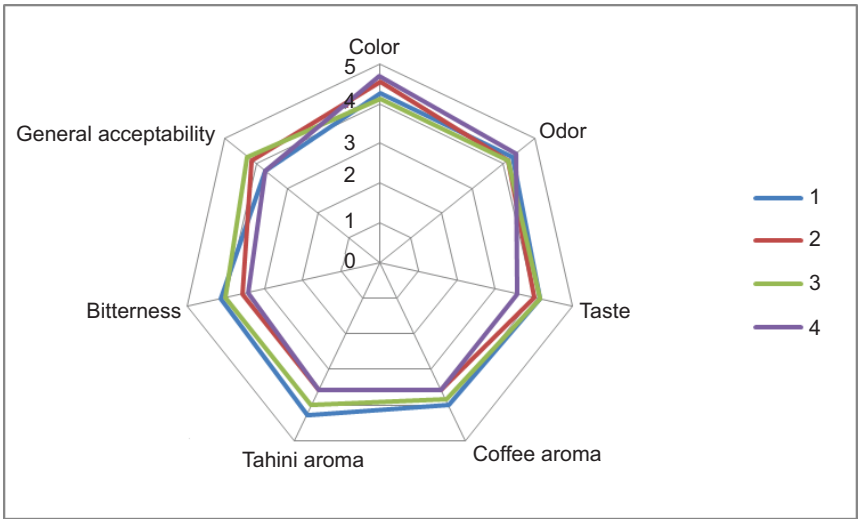

Figure 2. Results of sensory analysis of tahini–coffee beverages. Different combinations of roasted coffee extract (medium and dark) and tahini (roasted and double-roasted) were used in beverage samples. MCRT: medium-roasted coffee extract + roasted tahini; MCDRT: medium-roasted coffee extract + double-roasted tahini; DCRT: dark-roasted coffee extract + roasted tahini; DCDRT: dark-roasted coffee extract + double-roasted tahini.

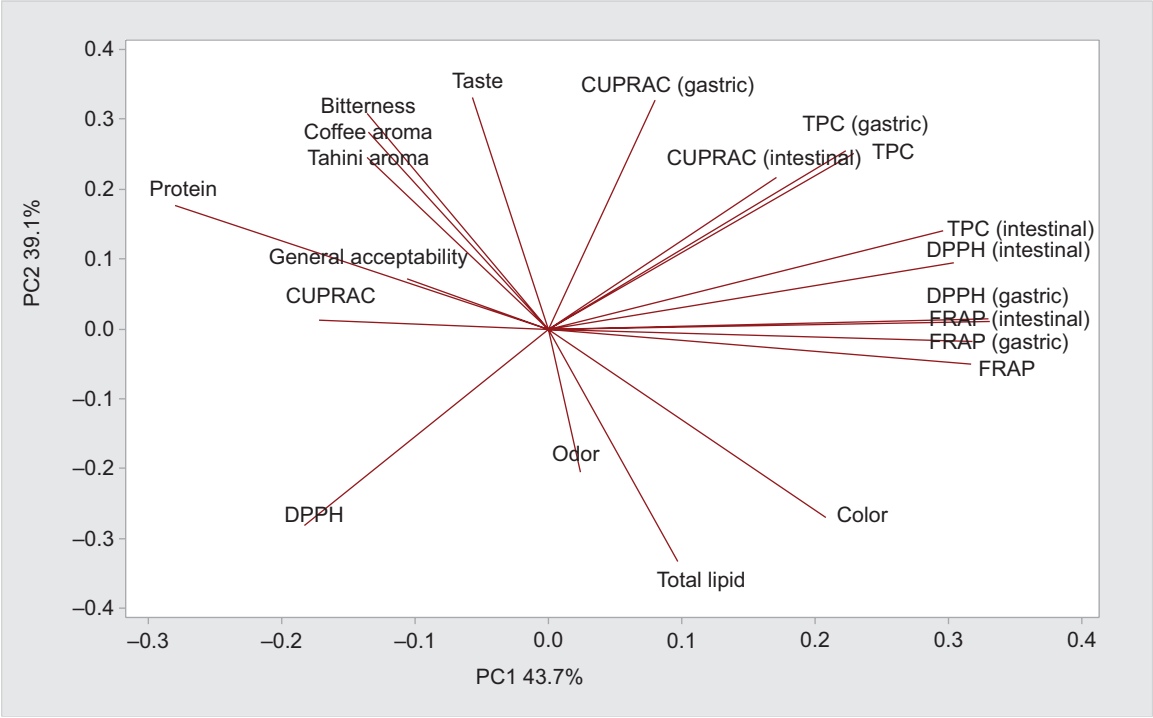

Figure 3. PCA loading plot of tahini–coffee beverages.

TPC values, except for the CUPRAC analysis values, which were also performed before digestion.

Protein values showed a strong negative correlation with the sensory evaluation parameter, color ($R^2 = -0.94$), and a positive correlation with the sensory evaluation parameter, bitterness ($R^2 = 0.76$). A strong negative correlation ($R^2 = -0.92$) was also observed between FRAP, antioxidant analysis, and protein values.

Strong and moderate positive correlations were found between total lipid values and color and odor parameters ($R^2 = 0.92$ and $R^2 = 0.56$, respectively), while negative correlations were found with other sensory parameters. Especially bitterness and taste parameters showed very strong negative correlations.

When interactions between sensory parameters were analyzed, a very strong positive correlation ($R^2 = 0.98$) was found between coffee aroma and tahini aroma and bitterness. This clearly demonstrates a positive interaction of these three parameters. When looking at the interactions with general acceptability parameter, a negative correlation was found with color, odor, coffee aroma, and tahini aroma, while positive correlations were observed with bitterness and taste.

The observed correlations among sensory attributes should also be interpreted in relation to physicochemical properties. For instance, bitterness and coffee aroma are associated with phenolic compounds and the Maillard reaction products, while sweetness perception is linked to total sugars content. Similarly, color parameters (L*, a*, and b*) can directly influence visual acceptability, and pH may affect flavor perception. Therefore, integrating sensory data with physicochemical indicators provides a more comprehensive understanding of product characteristics.

Principal component analysis

Principal component analysis was employed to reduce the complexity of the dataset and to enable a clearer and more interpretable visualization of the relationships among variables. The number of components retained for further statistical analysis was determined based on both dataset characteristics and proportion of total variance explained, as suggested by Cozzolino *et al.* (2019).

As illustrated in Figure 3, the loading plot indicates the influence of each variable (including texture, color, and sensory attributes) on principal components, while the score plot (Figure 4) displays the distribution of analyzed samples. In the PCA model, components with eigenvalues exceeding 1.00 were selected to ensure analytical robustness. The first six principal components collectively accounted for 100% of the total variance, with the first,

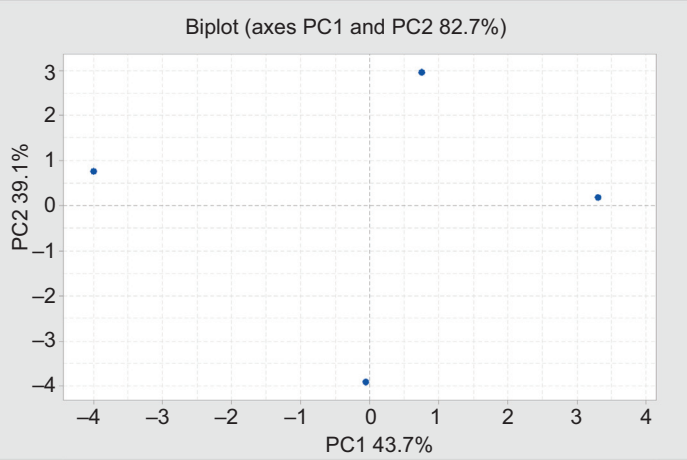

Figure 4. PCA score plot of tahini–coffee beverages. Different combinations of roasted coffee extract (medium and dark) and tahini (roasted and double-roasted) were used in beverage samples. MCRT: medium-roasted coffee extract + roasted tahini; MCDRT: medium-roasted coffee extract + double-roasted tahini; DCRT: dark-roasted coffee extract + roasted tahini; DCDRT: dark-roasted coffee extract + double-roasted tahini.

Table 8. Variance ratios (%) explained up to three principal components.

Variable	PC1	PC2	PC3
Eigenvalue	9.1666	8.2103	3.6231
Percent (%)	43.7	39.1	17.3
Cumulative	43.7	82.7	100
DPPH	–0.183	–0.281	0.108
FRAP	0.316	–0.050	0.130
CUPRAC	–0.172	0.012	0.448
TPC	0.229	0.252	0.010
DPPH (gastric)	0.330	0.010	0.006
FRAP (gastric)	0.318	–0.018	–0.141
CUPRAC (gastric)	0.080	0.327	–0.131
TPC (gastric)	0.223	0.255	0.061
DPPH (ıntestinal)	0.304	0.094	0.150
FRAP (ıntestinal)	0.329	0.014	0.042
CUPRAC (ıntestinal)	0.170	0.216	0.311
TPC (ıntestinal)	0.295	0.140	–0.105
Protein	–0.280	0.177	–0.081
Total lipids	0.097	–0.333	–0.018
Color	0.208	–0.270	0.042
Odor	0.024	–0.206	0.422
Taste	–0.058	0.331	–0.138
Coffee aroma	–0.135	0.282	0.222
Tahini aroma	–0.136	0.246	0.304
Bitterness	–0.136	0.308	0.117
General acceptability	–0.106	0.071	–0.486

second, and third components individually explaining 43.7%, 39.1%, and 17.33% of the variability, respectively (Table 8). Particularly, the first two components together explained 82.7% of the total variance (principal component 1 [PC1]: 43.7%; and principal component 2 [PC2]: 39.1%), effectively capturing major trends within the data.

Principal component 1 demonstrated a positive correlation with most of the antioxidant parameters, except for DPPH and CUPRAC values measured prior to digestion as well as with TPC values of post-digestion samples, total lipid content, and the sensory attributes of color and odor. In contrast, the remaining variables exhibited negative correlations with PC1. On the other hand, at the PC2 level, DPPH, total lipids, odor, and color parameters were negatively associated, whereas rest of the variables contributed positively. Movement along the direction of a vector indicates an increase in the corresponding variable, and samples located along this direction are characterized by higher values of that attribute. Conversely, movement in the opposite direction indicates an inverse relationship with variables.

The separation of samples observed in the PCA score plot was mainly driven by variables associated with roasting intensity and functional composition. Samples containing darker-roasted coffee and/or double-roasted tahini were more closely associated with color parameters related to darker appearance, higher total soluble solids, and selected antioxidant responses linked to the Maillard reaction-derived compounds. In contrast, samples prepared with medium-roasted materials were associated with higher TPC, lighter color coordinates, and improved sensory acceptability. These results indicate that roasting level was a major source of variation among formulations, while functional and sensory properties contributed to their multivariate discrimination. Chemometric approaches are widely used in food systems to identify hidden relationships between processing conditions and quality attributes.

Figure 4 illustrates the score plot generated by PCA, showing the distribution of beverage samples. As observed, MCRT and MCDRT samples are closely associated with positive scores along PC1, while DCRT and DCDRT samples display negative associations with this component. Additionally, MCRT, MCDRT, and DCRT samples are positively aligned along the PC2 axis, whereas DCDRT shows a negative contribution. These patterns were consistent with the findings presented for all measured variables and aligned with the interpretations discussed earlier. Overall, PCA successfully differentiated the biochemical and sensory profiles of beverage samples, offering a holistic representation of the distribution of key parameters.

The PCA model demonstrated strong explanatory power, with the first two principal components accounting for a substantial proportion of total variance, indicating that the model effectively captures the main variability within the dataset. Variables associated with antioxidant capacity (DPPH, FRAP, and CUPRAC) and TPC showed strong contributions to PC1, suggesting that this component primarily represents the bioactive profile of the beverages.

In contrast, sensory attributes and compositional parameters exhibited stronger associations with PC2, indicating that this component reflected sensory–compositional differentiation among samples.

The clustering pattern observed in the score plot further confirmed the discriminative ability of the model, as samples were clearly separated according to roasting intensity and formulation type. This indicated that the applied multivariate approach was suitable for capturing complex relationships between physicochemical, bioactive, and sensory properties in tahini–coffee beverage systems.

It should be noted that the present study did not include pure coffee or pure tahini controls, as the primary aim was to evaluate formulation-based differences within composite tahini–coffee systems, rather than to isolate the individual contributions of each component.

Therefore, the results should be interpreted in terms of relative differences among formulations rather than absolute contributions of coffee and tahini. While the inclusion of single-component controls could provide additional insight into synergistic or antagonistic interactions, the current design allows for the assessment of practical beverage formulations that more closely reflect real product development scenarios.

Future studies may further explore these interactions by incorporating simplified model systems to better distinguish the individual and combined effects of coffee and tahini components. Consequently, the respective contributions of coffee and tahini to TPC and antioxidant capacity could not be distinguished within the scope of this study.

Conclusions

This study comprehensively evaluated the physicochemical, bioactive, nutritional and sensory properties of tahini–coffee beverages formulated with commonly applied roasting degrees of tahini (roasted and double-roasted) and coffee (medium- and dark-roasted). The effects of roasting intensities on total proteins, total lipids, and total sugars content and accordingly total calorie value, TPC, TAC with DPPH, FRAP, and CUPRAC, and their changes during *in vitro* gastrointestinal digestion were examined systematically.

The findings indicate that double-roasted tahini significantly reduces protein levels, potentially because of thermal degradation or decreased solubility, but formulations containing double-roasted tahini have the highest total lipid content. In addition, with approximately 86–121 kcal of energy/200-mL serving, tahini–coffee beverage is much lower in calories than similar milk-flavored coffee products and may be considered a snack rather than a main meal in daily diet. TAC was significantly affected by both roasting conditions and digestion stages. Specifically, decrease in TPC during the stomach phase was followed by a notable increase during the intestinal phase, which is associated with the potential release of polyphenolic compounds under intestinal conditions. The roasting levels of coffee and tahini used in beverage production also affected their TAC values. Additionally, the same increasing trend was observed in DPPH, FRAP, and CUPRAC analyses before and after *in vitro* gastrointestinal digestion. Correlation analysis revealed strong and significant relationships between antioxidant capacity results of different stages of digestion and TPC values.

From a practical product development perspective, the results suggest that formulations containing medium-roasted coffee combined with roasted or double-roasted tahini may offer a balanced quality profile in terms of phenolic content, antioxidant potential, and sensory acceptability. In contrast, darker roasting conditions may be preferred when stronger color intensity, higher total soluble solids, or more pronounced roasted flavor notes are desired. Therefore, roasting level may serve as a practical formulation tool to tailor tahini–coffee beverages according to targeted consumer preferences and functional positioning. These findings provide a useful basis for developing a future plant-based coffee beverage with differentiated sensory and compositional profiles.

In general, the findings emphasize that the degree of roasting plays a significant role by affecting the nutritional and bioactive profiles and sensory appeal of tahini-based coffee beverages. The present findings extend current knowledge on sesame-based beverage systems and support tahini as a multifunctional ingredient for next-generation plant-based coffee beverages. Multivariate statistical approaches, such as PCA and correlation analysis, provided a comprehensive perspective on the interactions between compositional and sensory characteristics. Tahini-based milk alternative is identified as a promising ingredient for developing plant-based beverages, particularly for lactose- and gluten-free formulations. The findings of this study suggest that such formulations may contribute to the development of functional beverages with favorable physicochemical and bioactive properties, although further studies are required to confirm their potential health effects and consumer acceptance at a larger scale.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author.

Mandatory Disclosure on Use of Artificial Intelligence

ChatGPT (OpenAI) was used solely for language editing and improvement of readability during manuscript preparation. The author takes full responsibility for the scientific content, interpretation, and conclusions presented in this manuscript.

Author Contributions

Elif Nimet Havva Pehlivan: writing, investigation, formal analysis; Senanur Durgut Malçok: writing, investigation, and formal analysis; and Senem Suna: writing – review & editing, and formal analysis. All authors reviewed and finalized the manuscript.

Conflicts of Interest

The authors declared no competing interest.

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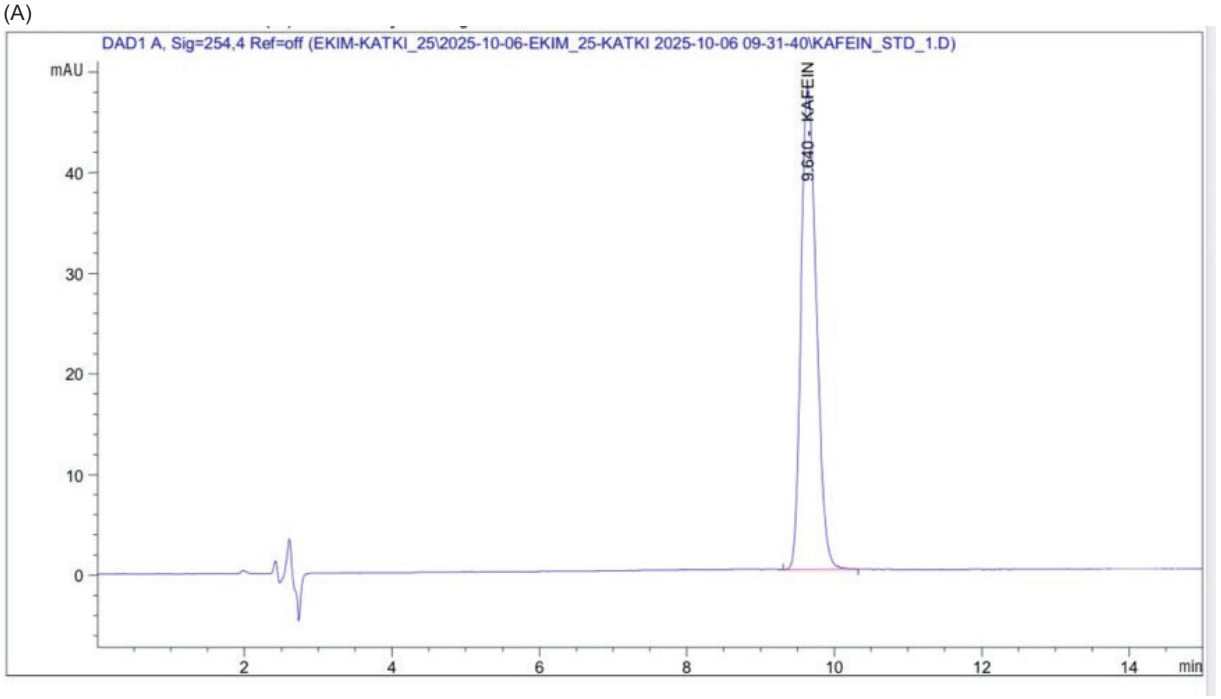
Supplementary

(A)



(B)

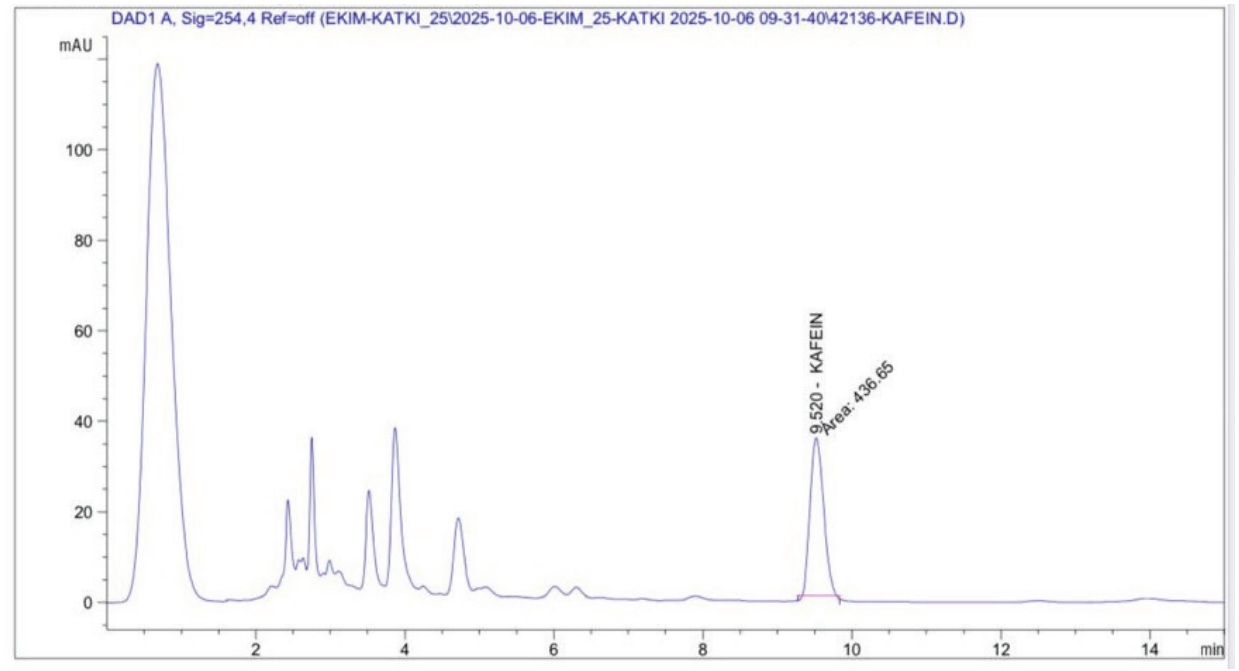
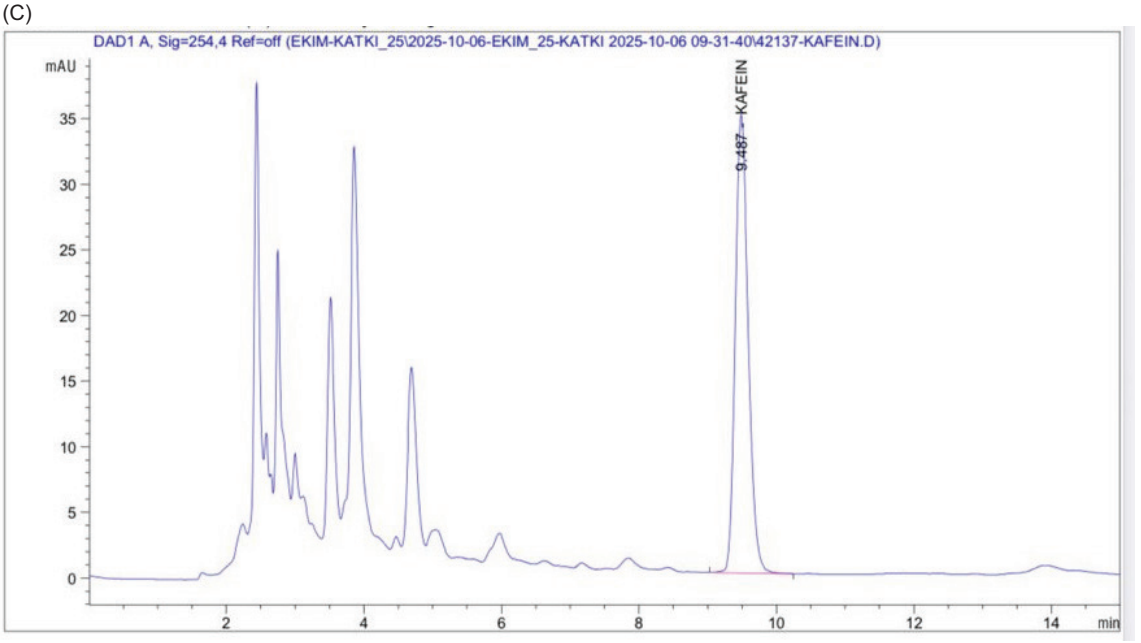


Figure S1. The chromatograms for the standard (A) and samples; MCRT: Medium roasted coffee + roasted tahini (B), MCDRT: Medium roasted coffee + double roasted tahini (C), DCRT: Dark roasted coffee + roasted tahini (D), DCDRT: Dark roasted coffee + double roasted tahini (E).

(C)



(D)

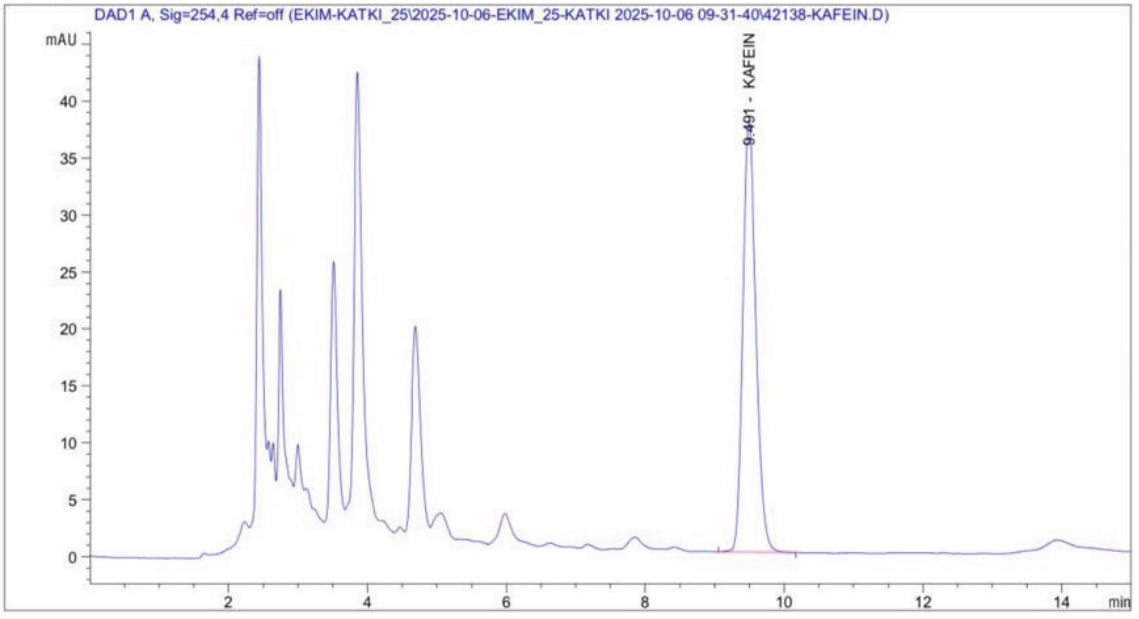


Figure S1. (Continued) The chromatograms for the standard (A) and samples; MCRT: Medium roasted coffee + roasted tahini (B), MCDRT: Medium roasted coffee + double roasted tahini (C), DCRT: Dark roasted coffee + roasted tahini (D), DCDRT: Dark roasted coffee + double roasted tahini (E).

(E)

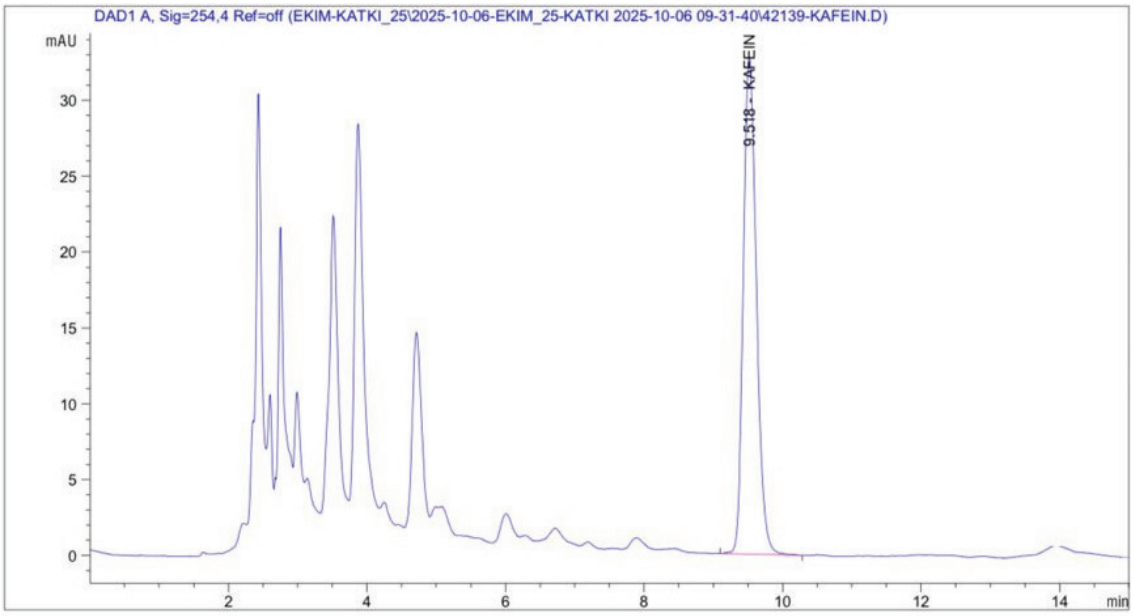


Figure S1. (Continued) The chromatograms for the standard (A) and samples; MCRT: Medium roasted coffee + roasted tahini (B), MCDRT: Medium roasted coffee + double roasted tahini (C), DCRT: Dark roasted coffee + roasted tahini (D), DCDRT: Dark roasted coffee + double roasted tahini (E).