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Effects of brewing conditions on the sensory and chemical properties of Turkish black tea and their interrelationships

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This study investigated the effects of different brewing conditions on the sensory and chemical properties of Turkish black tea and examined the relationships among the related parameters. The brewing variables evaluated were teapot type, brewing method, teapot spout condition, brewing time, and brewing water temperature. The brewed tea samples were evaluated by seven trained panelists for colour, astringency, and flavour and analysed for major chemical quality parameters, including total phenolic content (TPC), caffeine, theaflavins (TF), thearubigins (TR), brew colour indices, and L*a*b values. A total of 2,688 cups of brewed black tea were prepared, of which 672 were control and 2,016 were test samples, and were evaluated by seven trained panelists. Among the sensory attributes, colour was the most responsive parameter, being significantly affected by teapot type and brewing water temperature ($p < 0.01$), whereas astringency and flavour were not significantly influenced by the tested brewing conditions. In the chemical analyses, brewing water temperature was the most influential factor, significantly affecting TPC, caffeine, TF, TR, total colour in the brew, brightness in the brew, and a* ($p < 0.01$). Teapot type, brewing method, teapot spout condition, and brewing time also showed selective effects on specific chemical variables. Correlation analysis further showed that sensory colour was positively associated with TPC, caffeine, TF, TR, brightness in the brew, and total colour in the brew ($p < 0.01$), whereas astringency and flavour showed limited or no direct associations with the analysed chemical parameters. By examining Turkish-style brewing variables together with sensory and chemical profiling, this study provides novel evidence on sensory–chemical relationships in black tea and offers practical guidance for optimising brewing conditions in research and traditional tea preparation.

Keywords Black tea, Brewing conditions, Sensory analysis, Total phenolics, Caffeine, Theaflavins, Thearubigins

Tea plant (*Camellia sinensis*) is an evergreen, woody, perennial plant that grows in humid climates and prefers slightly acidic soils[1]. The most common tea types are black, green, white, and oolong tea, etc. Başaran[2]. White and green teas are generally considered unfermented or minimally oxidised, oolong tea semi-fermented or partially oxidised, and black tea fully fermented or extensively oxidised, with these categories mainly reflecting differences in enzymatic oxidation during tea processing[3]. Although tea consumption varies across geographical and cultural settings, black tea is the most widely consumed tea type in the world[4].

The production process of black tea generally includes harvesting, withering, rolling, oxidation, drying, and sorting-packaging, although these stages may vary depending on raw material characteristics, processing

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infrastructure, and consumer preferences[5]. These processes significantly affect the concentration of chemical components in tea and, consequently, its sensory properties[6,7]. For example, withering at high temperatures or for prolonged periods may lead to undesirable changes in the levels of theaflavins (TF) and thearubigins (TR), which influence sensory attributes such as brightness and astringency in black tea[8,9]. Likewise, improper oxidation may result in the formation of highly polymerised substances that increase turbidity in the brew[10]. Samanta et al.[11] reported that TF levels decrease and TR levels increase as oxidation time is prolonged, negatively affecting brew brightness and astringency. Black tea is also an important source of caffeine and polyphenols, both of which are closely linked to tea quality and consumer perception[12–14]. However, high levels of these compounds do not always correspond to desirable sensory quality. Zhang et al.[15], for instance, noted that teas rich in polyphenols may still exhibit pronounced bitterness.

Despite the importance of black tea in daily life, there is still no clear consensus on optimal brewing conditions, as brewing practices vary according to cultural habits and individual preferences[16]. Black tea quality is commonly evaluated through sensory characteristics such as colour, brightness, astringency, and flavour, as well as through chemical parameters including caffeine, tannins, polyphenols, TF, TR, and volatile compounds[17,18]. Recent studies have also shown increasing interest in intelligent sensory evaluation methods for black tea, particularly electronic nose and electronic tongue systems. These approaches can provide objective instrumental patterns related to aroma and taste and have been used for black tea classification, quality-grade discrimination, and prediction of sensory quality. For example, feature fusion of electronic nose and electronic tongue responses has improved the classification of different grades of black tea, while more recent studies have combined GC-E-nose, electronic tongue, electronic eye, near-infrared spectroscopy, and data-fusion methods to evaluate black tea quality grades more objectively[19–22]. However, these intelligent sensory approaches are mainly directed at classification, grading, or instrumental prediction, whereas fewer studies have examined how traditional brewing variables simultaneously influence trained sensory scores and chemical quality parameters. Previous studies have examined the effects of brewing conditions on black tea infusions, but these have generally focused on single or limited factors, such as infusion time or water temperature, and have often evaluated selected chemical or sensory parameters separately[15,18,23,24]. However, evidence remains limited on how multiple brewing variables act together to shape both the sensory and chemical properties of black tea, and on whether changes in chemical composition are consistently reflected in sensory perception.

This study was conducted in Türkiye, where tea has both cultural and economic importance. According to Food and Agriculture Organization[25] data, Türkiye ranks fourth in the world in tea production and first in per capita tea consumption, with 4 kg per person. Tea is widely regarded in Türkiye as an important means of socialisation and an indicator of hospitality and sincerity[26]. It is also a strategic agricultural product cultivated in the Black Sea Region and largely processed according to the orthodox (rotorvan integrated) method[27].

Although black tea production may be standardised to a considerable extent, brewing conditions such as water temperature and brewing time can still affect the extraction of chemical compounds and, in turn, the sensory properties of the final infusion. A structured evaluation combining sensory and chemical measurements is therefore important for interpreting food quality in a more integrated manner, as multi-component assessment frameworks can improve the robustness of food-related evaluation designs[28]. More broadly, integrated quality evaluation is also relevant to food industry contexts in which processing conditions, product quality, resource use, and sustainability are increasingly considered as interconnected dimensions of food systems[29]. Accordingly, this study tested the hypothesis that Turkish-style brewing variables would produce parameter-specific changes in the sensory and chemical profile of black tea rather than exerting uniform effects across all measured attributes.

Materials and methods

Tea samples

The study was carried out on commercial black teas belonging to four different brands produced by tea enterprises operating in Rize, Türkiye. The samples were coded as Brand A, Brand B, Brand C and Brand D throughout the study. The selected brands represent commercially important and widely available Turkish black teas. Brand A accounts for approximately 50–55% of the dry tea market in Türkiye, while Brand B has an annual fresh tea processing capacity of approximately 275 thousand tonnes. Brands C and D are also well-known commercial brands with national and international market presence. These brands are sold in many local and national grocery stores and on e-commerce platforms operating in Türkiye. All four products were packaged Turkish black teas produced from tea leaves grown in the Eastern Black Sea Region and processed using the orthodox/rotorvan-integrated black tea manufacturing method.

For each coded brand, twenty packages (500 g each) with the same production date and batch number were obtained from retail markets and/or production companies in their original packaging, giving a total sample amount of 10 kg per brand. Using packages with the same production date and batch number was intended to minimise within-brand variation and improve repeatability. Detailed factory-level processing parameters, such as exact rolling conditions, oxidation/fermentation duration and temperature, and drying parameters, were not available for all commercial products because these are manufacturer-specific production details. Therefore, the comparability of the test materials was ensured through their common production region, shared black tea category, similar commercial availability, identical package size, batch consistency, and common orthodox/rotorvan-integrated processing category. All samples were stored in a dry, dark environment at room temperature until analysis.

Establishment of the sensory panel and brewing procedure

As no standardised black tea brewing procedure has been universally adopted in Türkiye, a tea tasting panel and research team was established for this study on the basis of the literature and prevailing consumer practices. The team consisted of 12 individuals in total, including 7 tea-tasting panelists and 5 researchers. The panelists

were responsible for the sensory evaluation of the brewed tea samples, while the researchers were involved in the planning and implementation of the study. The selection of the tea-tasting panelists followed the guidelines of TS EN ISO 8586, "Sensory analysis – General guidelines for the selection, training and monitoring of selected assessors and expert sensory assessors" (TS EN ISO 8586/2014)[30]. The 7 panelists were selected from a pool of 23 candidates. Their ages ranged from 25 to 55 years. All panelists had previously received certified training in tea tasting and had active experience in the tea sector. They also confirmed their willingness to participate in the sensory analyses and to devote sufficient time to the study. Before the sensory evaluations began, both the panelists and the researchers were informed about the aim, scope, and tasting procedures of the study. Any uncertainties regarding the evaluation process were clarified through discussion. In addition, a panel leader was appointed from among the panelists to support the organisation of the tasting sessions.

Brewing parameters and procedure

The brewing parameters used in this study were determined on the basis of the relevant literature, common tea consumption practices in Türkiye, and the experience of the trained panelists. The parameters examined were teapot type, teapot spout condition, brewing method, brewing water temperature, and brewing time (Fig. 1). Chrome-steel and porcelain teapots were selected because they are among the most commonly used teapot materials in Turkish black tea preparation and may differ in heat retention and heat transfer characteristics. The two brewing methods were included to reflect the common practical variation in the order of adding dry tea and hot water during Turkish-style brewing. Teapot spout condition was evaluated as open or closed because closing the spout may promote the retention and condensation of water vapour inside the upper teapot and may limit air exchange during brewing, whereas leaving it open allows vapour release and greater contact with ambient air. The selected brewing water temperatures were intended to represent a lower extraction condition (75 °C) and two near-boiling conditions commonly relevant to Turkish black tea preparation (90 and 95 °C). The brewing times of 15 and 20 min were chosen to reflect the relatively long infusion periods used in Turkish double-teapot brewing and to test whether a moderate extension of brewing time within this customary range affected sensory and chemical properties.

Two teapot types commonly used in Türkiye for black tea brewing were included in the study: chrome-steel and porcelain teapots. Both consisted of two parts: a larger lower pot used for boiling water and a smaller upper pot used for brewing the tea. The teapot spout condition was evaluated at two levels: open and closed. In the open condition, the lid at the spout of the upper pot was left open during brewing, whereas in the closed condition, this lid was kept closed. Two brewing methods commonly preferred in Türkiye were tested: (i) adding the tea sample (powder) to the upper pot first and then pouring hot water over it, and (ii) adding hot water to the upper pot first and then adding the tea sample. Brewing water temperatures were set at 75, 90, and 95 °C, and brewing times were set at 15 and 20 min.

Brewing was carried out according to Basaran et al.[31]. Briefly, 2 L of ultrapure water was placed in the lower pot and heated to boiling, while the upper pot was kept empty. Then, 30 g of tea sample and 500 mL of water at the selected brewing temperature were added according to the relevant brewing method. Water temperature was monitored using a calibrated digital thermometer (Interlab, İstanbul, Türkiye). The tea was brewed on the stove over low heat for 15–20 min, depending on the experimental condition. At the end of the brewing period, 40 mL of tea infusion was poured into a traditional thin-waisted tea glass and mixed with 40 mL of freshly boiled water to obtain a standard serving strength reflecting tea consumption practices in Türkiye (Fig. 2).

To minimise potential confounding effects and to standardise the brewing matrix, ultrapure water was used in all brewing trials. This choice was made because the composition of tap water may vary over time and such variation could affect extraction behaviour, sensory perception, and chemical analysis results. Therefore, ultrapure water was preferred to ensure that differences among samples were primarily attributable to the tested brewing conditions rather than to variation in water composition. The tea-to-water ratio, brewing volume, final dilution before sensory evaluation, and serving volume were kept constant across all experimental conditions. Water temperature was monitored using a calibrated digital thermometer, and the teapots were cleaned and dried after each brewing trial to avoid carry-over effects. Sensory evaluations were conducted in the same quiet

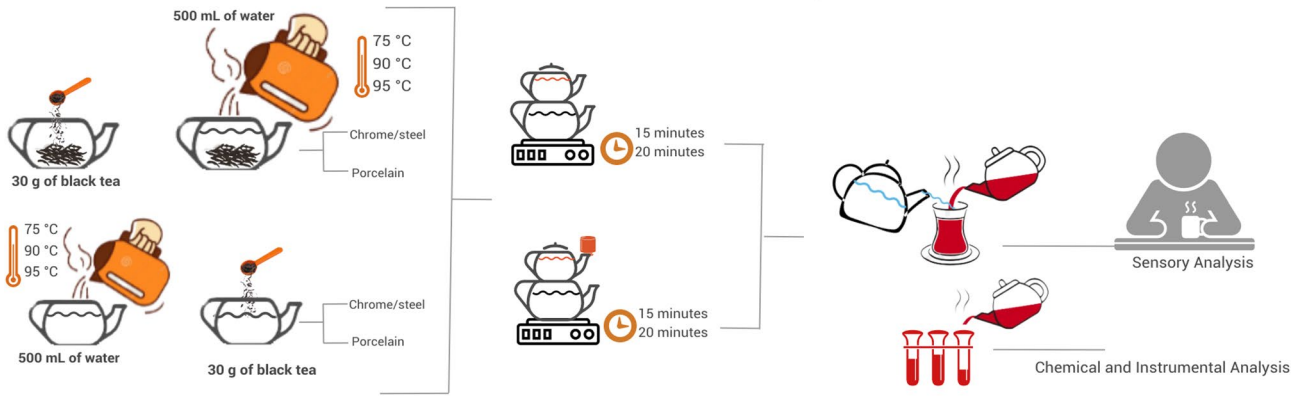


Fig. 1. Brewing parameters determined for black tea.



Fig. 2. Normal brewed tea (Brand D).

and well-ventilated room under daylight-supported ambient lighting, and the session schedule was standardised as far as panelist availability allowed.

Sensory analysis

Sensory evaluation of the brewed black tea samples was carried out using an in-house tea tasting procedure routinely employed by the private company producing Brand D. Brand D was used as the control sample because the reference score of this sensory procedure had been established for this product within the company's routine quality evaluation system. Accordingly, Brands A, B, and C were treated as test samples, while Brand D was used only as the reference/control sample in the sensory procedure. The sensory attributes evaluated were colour, astringency, and flavour, with flavour considered in relation to bitterness and sweetness.

In this procedure, each sensory parameter was assessed on a 5.00-point scale. Within the company method, a score of 3.40/5.00 is accepted as the reference value for Brand D for each parameter. After brewing, the tea samples were served to the panelists in traditional 80-mL thin-waisted tea glasses, and the panelists recorded their scores using the evaluation forms prepared for the study. Each brand was brewed twice under each experimental condition for replicate sensory evaluation. These duplicate sensory scores were used to assess repeatability at the level of the brewing trial.

The sensory sessions were planned to be conducted four times per day, three days per week (Monday, Wednesday, and Friday), with two sessions in the morning (10:00–12:00) and two in the afternoon (13:00–15:00). Minor adjustments to the session schedule were made when necessary according to panelist availability and health status. The evaluations were conducted in a quiet, well-ventilated room on the Recep Tayyip Erdoğan University campus.

Chemical analyses

Materials, chemicals and reagents

Acetonitrile (≥ 99.9%), gallic acid (≥ 99%) and caffeine (≥ 99%) were purchased from Sigma Chemical Co (St. Louis, MO). Methanol (≥ 99.9%), isobutyl methyl ketone (IBMK, ≥ 99%), HNO_3 (65%), $HClO_4$ (70–72%), oxalic acid (≥ 99%), and sodium bicarbonate (≥ 99.7%), were supplied from Merck (Darmstadt, Germany).

Total polyphenol analysis (TPC)

Total polyphenol content (TPC) was determined by an adapted Folin–Ciocalteu colorimetric method based on ISO 14502-1:2005[32]. Brewed tea samples were first filtered through coarse filter paper. Then, 1.0 mL of the filtrate was transferred into a 50-mL volumetric flask and diluted to volume with ultrapure water (MilliQ system, Millipore, Bedford, MA, USA). From this diluted extract, 1.0 mL was mixed with 5.0 mL of 10% (v/v) Folin–Ciocalteu reagent and 4.0 mL of 7.5% (w/v) sodium carbonate solution. The mixture was allowed to stand at room temperature for 60 min, and the absorbance was measured at 765 nm using a spectrophotometer (Shimadzu UV-160 VIS, Kyoto, Japan). TPC was quantified using a gallic acid calibration curve. Analyses were performed in duplicate.

Caffeine analysis

Caffeine analysis was performed by an adapted high-performance liquid chromatography (HPLC) method based on TS ISO 10727:2004[33]. Brewed tea samples were first filtered through coarse filter paper. Then, 1.0 mL of the filtrate was transferred into a 50-mL volumetric flask and diluted to volume with ultrapure water. The diluted sample was filtered through a 0.45 µm membrane filter (Isolab, Wertheim, Germany) and transferred to an HPLC vial. Analyses were performed in duplicate. Caffeine determination was carried out using an HPLC system (Agilent 1260, Santa Clara, CA, USA) equipped with a diode-array detector and a C18 analytical column (5 µm, 250 × 4.6 mm). The mobile phase consisted of methanol: water (70:30, v/v), delivered at a flow rate of 1.0 mL/min. The injection volume was 20 µL, the column oven temperature was set at 40 °C, and detection was performed at 274 nm. Caffeine was quantified using an external caffeine calibration curve.

Theaflavin (TF) and thearubugin (TR) analysis

Theaflavin (TF) and thearubigin (TR) analyses were performed according to the method of Kaçar[34]. Brewed tea samples were cooled to room temperature and filtered through coarse filter paper. Then, 50 mL of the filtrate was

transferred into a separatory funnel and mixed with 50 mL of isobutyl methyl ketone (IBMK). After shaking for 1 min, the mixture was allowed to separate into two phases. The lower aqueous phase and the upper IBMK phase were collected separately. Analyses were performed in duplicate.

Solution A was prepared by transferring 4 mL of the IBMK phase into a 25-mL volumetric flask and making up to volume with methanol. Solution B was prepared by mixing 2 mL of the aqueous phase with 8 mL of distilled water in a 25-mL volumetric flask and making up to volume with methanol. Solution C was prepared by mixing 25 mL of the IBMK phase with 25 mL of 2.5% sodium bicarbonate solution in a separatory funnel, shaking the mixture, allowing the phases to separate, discarding the sodium bicarbonate phase, and then transferring 4 mL of the remaining IBMK phase into a 25-mL volumetric flask and making up to volume with methanol. Solution D was prepared by mixing 2 mL of the aqueous phase, 2 mL of saturated oxalic acid solution, and 6 mL of ultrapure water in a 25-mL volumetric flask and making up to volume with methanol. The absorbance values of solutions A, B, C, and D were measured at 380 and 460 nm using methanol: water (1:4, v/v) as the blank. TF and TR contents, as well as total colour, brightness, and colour density of the brew were calculated.

Colour analyses

The colour of the tea samples was measured using a Minolta CR–400 (Osaka, Japan) according to the Hunter (L, a, b) system in triplicate. In the Hunter system, colour values are represented as L* value (0: black; 100: white); a* value (-a: green; +a: red); and b* value (-b: blue; +b: yellow).

Statistical evaluation

The study data were imported into the R software program and analysed. The experimental unit was the independently brewed tea infusion prepared for each brand under each brewing-condition combination. The full factorial design consisted of two teapot types, two brewing methods, two teapot spout conditions, three brewing water temperatures, and two brewing times, giving 48 brewing-condition combinations per brand. Each brand was brewed twice under each condition, resulting in 384 independent brewed tea infusions in total. The reported total of 2,688 cups refers to the sensory servings evaluated by the seven trained panelists: 672 control servings for Brand D and 2,016 test servings for Brands A, B, and C. For sensory analysis, the scores given by the seven panelists were averaged for each brewing trial, and the resulting duplicate replicate means obtained for each brewing condition were used in the statistical evaluation. Repeatability was considered at the level of these duplicate brewing trials. Because the sensory dataset was based on replicate mean scores rather than on a formal panelist-level agreement design, inter-panelist agreement indices were not calculated. For chemical analysis, the same brewing trials were taken as the experimental unit, and technical replicate measurements obtained from each brewed tea sample were averaged before analysis. Brand D served as the reference/control brand only for the application of the in-house sensory procedure. To avoid treating the company reference product as a primary experimental comparator, Brand D was not included in the inferential statistical models, and the statistical interpretation focused on the effects of brewing parameters rather than brand-based quality ranking. The effects of brewing parameters on both sensory outcomes (colour, astringency, and flavour) and chemical outcomes were evaluated using general linear models with a factorial ANOVA structure. Effect sizes for the ANOVA models were reported as partial eta squared (ηp^2) (Table S1, S2). Teapot type, brewing method, teapot spout condition, brewing time, and brewing water temperature were included as fixed factors, while brand was included in the model as a control factor but was not interpreted as a primary variable of interest. The assumptions of the general linear models were evaluated by examining the normality of residuals and the homogeneity of variances. When significant main effects were detected, Tukey's post-hoc test was used for pairwise comparisons. Principal component analysis (PCA) was additionally performed as an exploratory multivariate tool to visualise patterns in the sensory and chemical profiles of black tea under different brewing conditions. Spearman's rho correlation analysis was used to examine the relationships among sensory parameters, among chemical parameters, and between sensory and chemical parameters based on matched values obtained from the same brewing trials. Statistical significance was set at $p < 0.01$ for the general linear models. Spearman's rho correlations were reported at two significance levels, $p < 0.05$ and $p < 0.01$.

Results and discussion

Sensory properties of black tea under different brewing conditions

The sensory dataset used for statistical analysis consisted of replicate mean scores calculated from the evaluations of seven panelists for each brewing trial (Table 1).

Among the sensory attributes, colour was the most responsive parameter. Tea brewed in chrome-steel teapots had significantly higher mean colour scores than tea brewed in porcelain teapots ($p < 0.01$). This difference may be related to the thermal conductivity properties of the teapot materials, which could influence the extraction of colour-related compounds during brewing. The effect of teapot material on tea quality has also been noted in previous research. Öğüt[35] reported that teapot type may affect the taste, colour, and overall quality of tea, while Liao et al.[36] showed that different teapot materials can influence the sensory properties of brewed tea. Brewing water temperature also had a significant effect on colour ($p < 0.01$), with tea brewed at 95 °C receiving higher colour scores than tea brewed at 90 °C and 75 °C. This finding is consistent with previous studies suggesting that increasing brewing temperature promotes the extraction of compounds associated with brew colour[18,37,38]. By contrast, brewing method, teapot spout condition, and brewing time did not significantly affect colour scores ($p > 0.01$). Although visible differences in tea colour under different brewing methods have been noted in the literature[37], such an effect was not observed under the conditions of the present study. Similarly, although brewing time is generally considered an important factor in sensory quality[17], no significant difference was found between 15 and 20 min. This may be due to the fact that both brewing times are relatively long and close together.

Brewing parameters	Subparameters	Number of brews	Colour	Astringency	Flavour
			Mean ± SD (Min.–Max.)	Mean ± SD (Min.–Max.)	Mean ± SD (Min.–Max.)
Teapot type	Chrome–steel	144	3.50 ± 0.16 (3.20–3.80)[a]	3.20 ± 0.14 (3.00–3.80)[a]	3.20 ± 0.16 (3.00–3.80)[a]
	Porcelain	144	3.30 ± 0.13 (3.00–3.60)[b]	3.20 ± 0.12 (3.10–3.60)[a]	3.20 ± 0.10 (3.10–3.60)[a]
Brewing method	Tea on water	144	3.40 ± 0.14 (3.10–3.80)[a]	3.20 ± 0.14 (3.00–3.80)[a]	3.20 ± 0.10 (3.00–3.80)[a]
	Water over tea	144	3.40 ± 0.18 (3.00–3.80)[a]	3.20 ± 0.08 (3.00–3.80)[a]	3.20 ± 0.08 (3.00–3.70)[a]
Teapot spout	Open	144	3.40 ± 0.10 (3.00–3.60)[a]	3.20 ± 0.10 (3.10–3.60)[a]	3.20 ± 0.10 (3.00–3.60)[a]
	Close	144	3.40 ± 0.12 (3.00–3.80)[a]	3.20 ± 0.15 (3.00–3.80)[a]	3.20 ± 0.14 (3.00–3.80)[a]
Brewing time	15 min	144	3.40 ± 0.10 (3.10–3.80)[a]	3.20 ± 0.12 (3.00–3.80)[a]	3.20 ± 0.12 (3.00–3.80)[a]
	20 min	144	3.40 ± 0.09 (3.00–3.80)[a]	3.20 ± 0.11 (3.00–3.80)[a]	3.20 ± 0.12 (3.00–3.80)[a]
Brewing water temperature	95 °C	96	3.50 ± 0.15 (3.20–3.80)[a]	3.20 ± 0.15 (3.00–3.80)[a]	3.20 ± 0.16 (3.00–3.80)[a]
	90 °C	96	3.30 ± 0.01 (3.00–3.80)[b]	3.20 ± 0.02 (3.10–3.60)[a]	3.20 ± 0.08 (3.10–3.60)[a]
	75 °C	96	3.30 ± 0.12 (3.10–3.60)[b]	3.20 ± 0.13 (3.00–3.60)[a]	3.20 ± 0.08 (3.00–3.60)[a]

Table 1. Evaluation of tasting analyses of black tea according to brewing parameters. Min=Minimum. Max=Maximum. [a, b] Different letters in the same group indicate statistically significant differences ($p < 0.01$).

Astringency and flavour did not differ significantly across the tested brewing conditions ($p > 0.01$), suggesting that the sensory impact of the brewing variables was more evident in colour perception than in taste-related attributes. In contrast to the present results, Yu et al.[18] reported that bitterness, astringency, and sourness in black tea increased with increasing brewing water temperature and brewing time. Similarly, Zhao et al.[39] found that higher brewing water temperatures increased both the number and diversity of flavour compounds in the brew. Polat et al.[17] also reported significant differences in several sensory properties of black tea, including colour, brightness, clarity, astringency, aroma, and bitterness, depending on brewing time. The difference between the present findings and those reported in previous studies may be related to differences in tea material, brewing design, sensory evaluation procedure, or the range of brewing conditions examined. It is also possible that the brewing conditions tested in the present study were not sufficiently distinct to produce a clear separation in astringency and flavour scores.

Figure 3A–E presents the PCA plots of the sensory profiles of black tea samples under different brewing conditions. The first two principal components explained 77.9% of the total variance, with PC1 and PC2 accounting for 44.0% and 33.9%, respectively. Although this cumulative variance indicates that the first two dimensions captured a substantial proportion of the sensory variation, the PCA plots did not reveal a strong or clearly separated clustering pattern according to the brewing parameters. In most cases, the confidence ellipses showed considerable overlap, suggesting that the brewing factors did not generate distinct overall sensory profiles. A slight directional shift was observed for some parameters, particularly teapot type and brewing water temperature. Samples brewed in chrome-steel teapots and, to a lesser extent, those brewed at 95 °C tended to be distributed more towards the positive side of Dim1, which may reflect the stronger contribution of colour to sensory variation. However, these tendencies remained partial rather than definitive. By contrast, brewing method, teapot spout condition, and brewing time showed broad overlap and did not produce a clear multivariate separation among samples. Overall, the sensory PCA supported the univariate findings: the brewing parameters did not generate clearly separated sensory profiles, although teapot type and brewing water temperature showed slight directional effects mainly associated with colour.

Chemical properties of black tea under different brewing conditions

Table 2 displays the levels of TPC, caffeine, TF, TR, darkness in the brew, brightness in the brew, total colour in the brew, and L*a*b levels in black tea prepared under different brewing parameters.

Teapot type had a significant effect on several chemical variables. Tea brewed in chrome-steel teapots had significantly higher mean TPC, caffeine, TF, TR, total colour in the brew, and L* values than tea brewed in porcelain teapots ($p < 0.01$). This finding suggests that teapot material may influence extraction efficiency, possibly through differences in heat transfer during brewing. Chrome-steel teapots may transfer heat more rapidly and help maintain a more stable extraction environment, thereby facilitating the release of phenolic compounds, caffeine, TF, and TR into the infusion. By contrast, the effect was not uniform across all colour-related variables, indicating that teapot material influenced selected extraction and colour parameters rather than the entire chemical profile. Thus, the influence of teapot material was more evident in the concentration of extracted compounds than in all colour-related indicators taken together. The elevated levels of TF and TR,

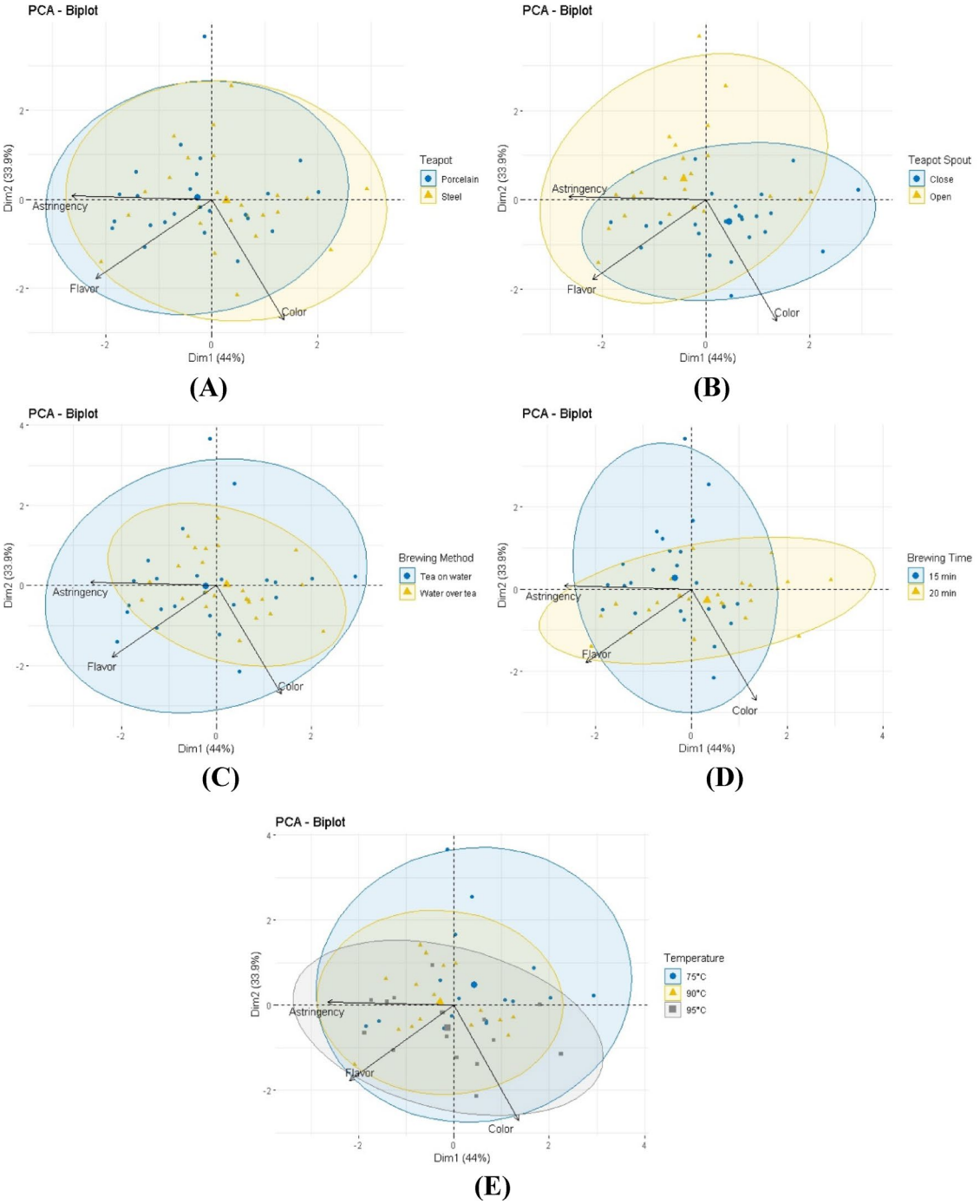


Fig. 3. PCA analysis of sensory parameters.

which are known to contribute to brew colour, together with the higher L* values observed in tea brewed in chrome-steel teapots, may help to explain the significant differences in colour observed in the sensory analysis. Liao et al.[36] likewise showed that the material of the brewing vessel could influence the chemical characteristics of tea infusions, although the direction and magnitude of these effects may vary according to the materials compared.

Brewing method had a limited effect on the chemical profile. Only caffeine and brightness in the brew differed significantly between the two methods ($p < 0.01$), while the remaining chemical parameters showed no consistent response. These results suggest that changing the order of tea and water addition influenced selected extraction-related variables rather than producing a broad shift in the overall chemical profile of the brew. The fact that TF and TR values were very close to each other in both methods is also consistent with the absence of a significant difference in colour in the sensory analysis. Although mean caffeine and brightness in the brew differed significantly between brewing methods, these differences were not reflected in the sensory evaluation.

Brewing parameters	Subparameters	Number of brews	TPC (%	Caffeine (%)	TF (%)	TR (%)	Colour darkness in the brew (%)	Brightness in the brew (%)	Total colour in the brew (%)	L	a	b
			Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Teapot type	Chrome–steel	144	5.00 ± 0.90^{a}	2.00 ± 0.20^{a}	0.14 ± 0.03^{a}	17.5 ± 4.30^{a}	7.20 ± 0.40^{a}	8.80 ± 1.50^{a}	3.90 ± 1.20^{a}	19.9 ± 0.30^{a}	1.80 ± 0.20^{a}	-0.20 ± 0.08^{a}
	Porcelain	144	4.40 ± 0.80^{b}	1.80 ± 0.20^{b}	0.12 ± 0.02^{b}	15.3 ± 3.40^{b}	7.40 ± 0.50^{a}	8.60 ± 1.40^{a}	3.30 ± 0.90^{b}	19.8 ± 0.30^{b}	1.90 ± 0.10^{a}	-0.20 ± 0.08^{a}
Brewing method	Tea on water	144	4.90 ± 0.70^{a}	2.00 ± 0.30^{a}	0.10 ± 0.02^{a}	16.2 ± 3.10^{a}	7.40 ± 0.40^{a}	8.90 ± 1.10^{a}	3.40 ± 0.70^{a}	19.9 ± 0.30^{a}	1.80 ± 0.10^{a}	-0.20 ± 0.05^{a}
	Water over tea	144	4.70 ± 1.10^{a}	1.80 ± 0.20^{b}	0.10 ± 0.03^{a}	16.6 ± 4.80^{a}	7.20 ± 0.60^{a}	8.50 ± 1.70^{a}	3.70 ± 1.30^{a}	19.8 ± 0.40^{b}	1.80 ± 0.10^{a}	-0.10 ± 0.10^{a}
Teapot spout	Open	144	4.80 ± 1.00^{a}	2.00 ± 0.20^{a}	0.10 ± 0.02^{a}	17.2 ± 5.00^{a}	7.10 ± 0.50^{b}	8.20 ± 1.70^{a}	3.90 ± 1.40^{a}	19.8 ± 0.08^{a}	1.80 ± 0.10^{a}	-0.20 ± 0.08^{a}
	Close	144	4.70 ± 0.80^{a}	1.70 ± 0.30^{b}	0.10 ± 0.03^{a}	15.6 ± 2.50^{a}	7.40 ± 0.40^{a}	9.30 ± 0.80^{a}	3.30 ± 0.60^{a}	19.9 ± 0.50^{a}	1.80 ± 0.10^{a}	-0.20 ± 0.08^{a}
Brewing time	15 min	144	4.40 ± 0.70^{b}	1.90 ± 0.40^{a}	0.10 ± 0.03^{a}	15.8 ± 3.00^{a}	7.10 ± 0.40^{a}	9.20 ± 1.20^{a}	3.40 ± 0.70^{a}	19.9 ± 0.30^{a}	1.80 ± 0.10^{a}	-0.20 ± 0.09^{a}
	20 min	144	4.90 ± 1.00^{a}	1.90 ± 0.50^{a}	0.10 ± 0.02^{a}	17.0 ± 4.80^{a}	7.40 ± 0.50^{a}	8.30 ± 1.50^{b}	3.80 ± 1.20^{a}	18.8 ± 0.30^{b}	1.80 ± 0.10^{a}	-0.20 ± 0.07^{a}
Brewing water temperature	95 °C	96	5.30 ± 0.50^{a}	2.20 ± 0.20^{a}	0.16 ± 0.02^{a}	19.6 ± 3.40^{a}	6.90 ± 0.20^{b}	8.90 ± 1.80^{a}	4.30 ± 1.20^{a}	19.5 ± 0.40^{a}	1.73 ± 0.10^{b}	-0.20 ± 0.10^{a}
	90 °C	96	4.70 ± 0.80^{b}	1.90 ± 0.20^{b}	0.13 ± 0.02^{b}	16.8 ± 3.00^{b}	7.20 ± 0.30$^{a, b}$	8.80 ± 1.60^{a}	3.60 ± 0.90^{b}	19.8 ± 0.10^{a}	1.92 ± 0.10^{a}	-0.20 ± 0.08^{a}
	75 °C	96	4.10 ± 0.90^{b}	1.70 ± 0.20^{b}	0.10 ± 0.01^{c}	12.8 ± 2.10^{c}	7.70 ± 0.20^{a}	8.60 ± 0.50^{b}	2.80 ± 0.30^{c}	19.9 ± 0.30^{a}	1.98 ± 0.10^{a}	-0.20 ± 0.05^{a}

Table 2. Total polyphenol, caffeine, theaflavin, thearubigin, colour darkness in the brew, total colour in the brew, brightness in the brew and L*a*b levels of black tea according to brewing parameters. $^{a, b,c}$Different letters in the same group indicate statistically significant differences, TPC= Total phenolic, TF=Theaflavin, TR=Thearubigin.

Hajiaghaalipour et al.[40] also reported that extraction conditions may influence the recovery of phenolic constituents in black tea infusions depending on brewing procedure and duration.

Teapot spout condition produced only selective effects on the chemical profile. Caffeine was significantly higher when the spout was left open, whereas colour darkness in the brew was significantly higher when the spout was closed ($p < 0.01$). The higher caffeine content observed under the open-spout condition may be partly explained by vapour release and partial water loss during brewing, which could create a concentration effect and increase the measured level of soluble compounds in the infusion. In addition, leaving the spout open may allow greater air exchange and modify heat and mass transfer conditions during extraction. Conversely, closing the spout may promote vapour retention and condensation inside the upper teapot, which may help explain the higher colour darkness observed under the closed-spout condition. However, because the remaining chemical variables and all sensory attributes showed no consistent response, and because evaporation rate and oxygen exposure were not directly measured, teapot spout condition should be interpreted as a selective factor rather than a major determinant of the overall sensory or chemical profile under the tested conditions.

Brewing time had a generally limited effect. TPC, brightness in the brew, and L were significantly affected by brewing time ($p < 0.01$), whereas most other chemical variables remained unchanged. This may be because both 15 and 20 min represent relatively long infusion periods, reducing the likelihood of sharp differences between the two conditions. The limited influence of brewing time on most chemical variables is also consistent with the absence of a significant effect of brewing time on colour, astringency, and flavour in the sensory analysis. Similar observations have been reported in the literature. Friedman[41] found that infusion times between 3 and 20 min did not result in a significant difference in TF levels. Ramalho et al.[23] reported that TPC in black tea infusions changed significantly during the early stages of brewing, whereas longer infusion periods did not always produce further marked differences. Kelebek[42] and Yu et al.[18] likewise reported that shorter brewing times were associated with higher L* values. Salman et al.[24] reported that brewing time in Turkish black tea significantly affected TPC and caffeine, but not TF, TR, brightness, or total colour levels.

The brewing water temperature was the most influential factor affecting the chemical profile of black tea. Among the analysed variables, TPC, caffeine, TF, TR, total colour in the brew, brightness in the brew, and the a value were significantly affected by brewing water temperature ($p < 0.01$). In general, increasing the brewing water temperature led to higher levels of TPC, caffeine, TF, TR, and total colour in the brew, while brightness in the brew was higher at 90 and 95 °C than at 75 °C. By contrast, the a value decreased at the highest temperature. TF showed the clearest temperature-dependent pattern, increasing progressively from 75 to 90 and 95 °C, and a similarly strong temperature effect was also observed for TR. These findings indicate that higher brewing temperatures promoted the extraction of major colour- and phenolic-related compounds into the infusion. Mechanistically, higher brewing temperatures may increase molecular diffusion, improve the solubility of phenolic compounds and alkaloids, and accelerate the transfer of oxidised polyphenolic pigments such as TF and TR from tea particles into the aqueous phase. In contrast, colour darkness in the brew was higher at lower temperatures, which may be associated with differences in the extraction and diffusion behaviour of colour-related compounds under milder brewing conditions. The increase in TF at higher temperatures may also help to explain the higher brightness and total colour values observed in the brew. Temperature is known to enhance the dissolution and diffusion of chemical compounds during tea brewing, and the present findings are consistent with previous studies reporting that increasing brewing temperature promotes the release of phenolic and colour-related constituents in tea infusions[18,39]. Similarly, Almeida et al.[43] reported that phenolic concentrations in brewed black tea increased with increasing temperature, whereas Kelebek[42] found that temperature was associated with changes in colour coordinates during black tea brewing. Zhao et al.[39] also explained differences in TPC and L*a*b values in tea samples brewed under different temperature conditions in a similar way.

Figure 4A–E presents the PCA plots of the chemical profiles of black tea samples under different brewing conditions. The first two principal components explained 61.2% of the total variance, with PC1 and PC2 accounting for 43.3% and 17.9%, respectively. Although this proportion indicates that the first two dimensions captured a substantial part of the chemical variation, clear clustering was observed mainly according to brewing water temperature. In particular, samples brewed at 75 °C tended to be positioned towards the positive side of PC1 and were associated with higher a*, b*, and colour darkness in the brew values, whereas higher-temperature samples were more closely associated with TF, TR, and total colour in the brew. PC2 was influenced mainly by variation related to brightness in the brew. By contrast, teapot type, brewing method, teapot spout condition, and brewing time did not produce a clear separation of samples in the PCA plots. Overall, the chemical PCA confirmed brewing water temperature as the main factor shaping the chemical profile, whereas the other brewing parameters produced only limited multivariate differentiation.

Sensory and chemical properties of black tea and their interrelationships

Among the sensory parameters, Spearman's rho analysis showed a weak positive correlation between colour and astringency ($\rho = 0.17$; $p < 0.01$) and a moderate positive correlation between flavour and astringency ($\rho = 0.54$; $p < 0.01$). By contrast, no significant correlation was found between colour and flavour ($\rho = 0.04$; $p > 0.01$). These findings suggest that astringency was more closely associated with flavour than with colour under the conditions of the present study. Wang et al.[44] reported a positive correlation between the flavour and astringency of black tea.

The strongest positive correlation was observed between TR and total colour in the brew ($p < 0.01$), followed by strong positive correlations between TF and TR ($p < 0.01$), TF and total colour in the brew ($p < 0.01$), and TF and brightness in the brew ($p < 0.01$). TPC and caffeine were also positively correlated with TF, TR, and total colour in the brew, indicating that the release of phenolic and stimulant compounds was broadly associated with increased colour development in the infusion. By contrast, colour darkness in the brew showed significant negative correlations with TPC, caffeine, TF, TR, and total colour in the brew, whereas the a* value was negatively

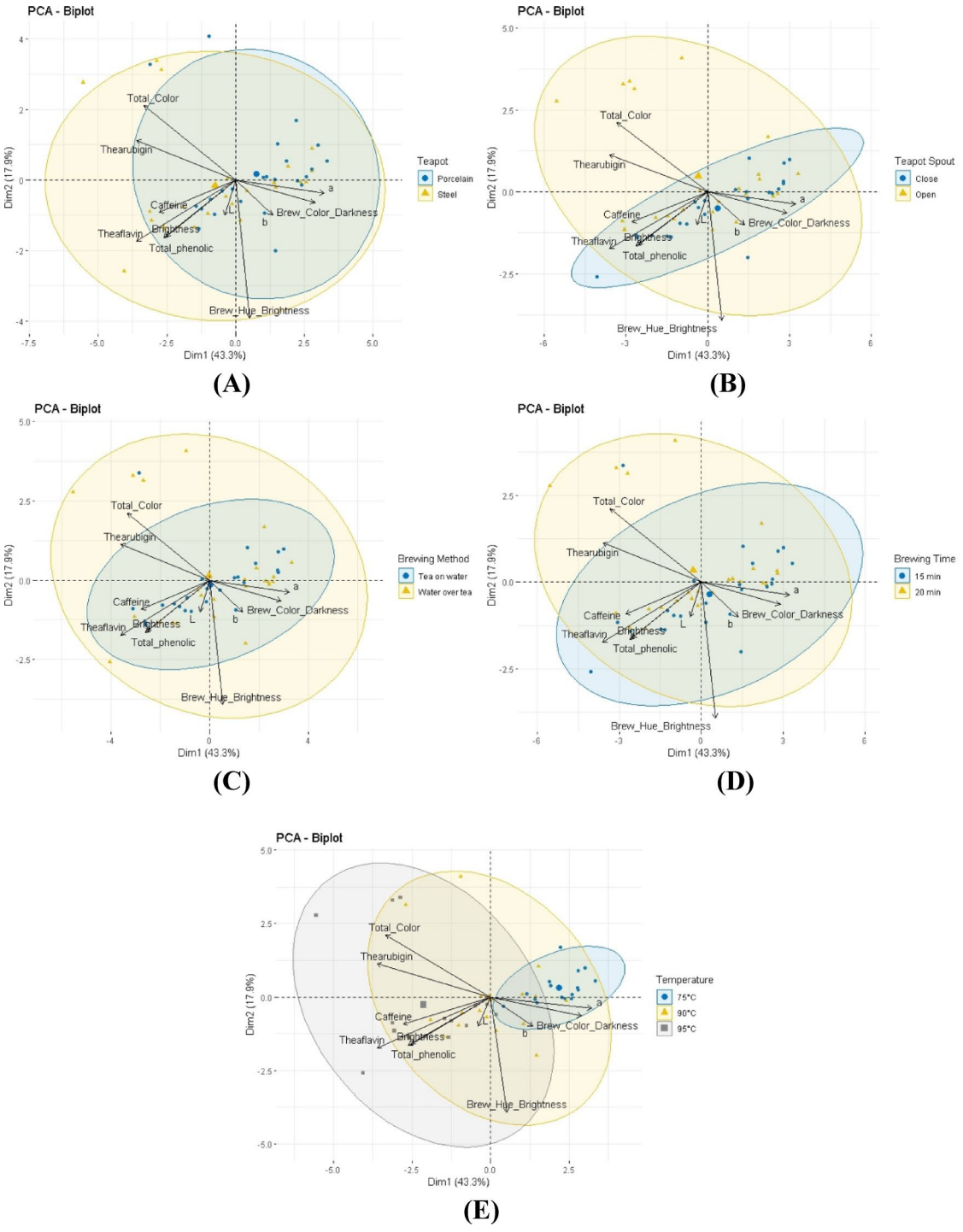


Fig. 4. PCA analysis of chemical parameters.

associated with most major chemical constituents and positively associated with colour darkness in the brew. L* showed only limited associations with the other chemical variables. Overall, these correlations suggest that the chemical profile of the brew was shaped by a coordinated increase in phenolic compounds, caffeine, TF, TR, and total colour, while darker and redder colour tendencies followed a partly different pattern. These patterns may partly relate to the weak positive association observed between colour and astringency in the sensory analysis. The positive correlations of TF and TR with total colour in the brew are broadly in line with previous reports, although the present findings also show some divergence from the literature. For example, Asil et al.[45] reported a positive correlation between TF and total colour and brightness, but a negative correlation between TR and brightness, whereas Polat et al.[17] reported a positive correlation between TF and L* and no correlation between a

and b* values. In contrast, the present study found no significant association between TF and L*, but a significant positive correlation between a* and b* (Fig. 5).

The correlation analysis indicated that sensory colour was the attribute most consistently associated with the chemical profile of black tea. Colour was positively correlated with TPC, caffeine, TF, TR, brightness in the brew, and total colour in the brew, and negatively correlated with colour darkness in the brew and a values ($p < 0.01$) (Fig. 6). These findings suggest that the chemical composition of the brew was reflected primarily in the colour attribute, whereas astringency and flavour were much less directly associated with the measured chemical variation under the conditions of the present study. TF and TR are the main compounds responsible for the colour and brightness of brewed black tea[46]. The positive correlations observed between colour and TF and TR are broadly consistent with previous studies[5,45,47]. TF and TR have also been associated with astringency and flavour in the literature[44,45]. However, no significant correlation was found between TF or TR and either astringency or flavour in the present study. Similarly, although caffeine has been linked to perceived astringency through synergistic interactions with other compounds[18,48], such a relationship was not observed here. Some previous studies have reported positive associations between TPC, caffeine, TF, and TR and broader sensory quality attributes of tea[44,45,49]. Polat et al.[17] likewise reported significant relationships between chemical constituents and sensory properties in Turkish black tea; however, in the present study these associations were reflected mainly in colour, whereas comparable relationships were not observed for astringency or flavour.

The weak or non-significant relationships observed for astringency and flavour indicate that the measured chemical indicators did not fully explain these sensory dimensions. This may be because TPC, caffeine, TF, and TR represent selected or broad chemical markers rather than the complete set of compounds responsible for taste perception. Astringency is not determined only by total phenolic concentration, but also by the composition of specific phenolic fractions, their degree of oxidation and polymerisation, interactions between polyphenols and caffeine, and their ability to interact with salivary proteins. Similarly, flavour perception depends not only on non-volatile compounds, but also on volatile aroma compounds, amino acids, sugars, organic acids, and interactions among taste-active constituents, which were not directly measured in the present study. Therefore, under the tested brewing conditions, the measured chemical variation was more closely aligned with sensory colour than with astringency or flavour.

Conclusion

This study showed that the effects of brewing conditions on Turkish black tea were not uniform across sensory and chemical parameters. Among the sensory attributes, colour was the most responsive variable, whereas astringency and flavour remained relatively stable under the tested conditions. By contrast, the chemical profile was more clearly affected by brewing conditions, particularly by brewing water temperature, with teapot type, brewing method, teapot spout condition, and brewing time producing more selective effects. Correlation analyses

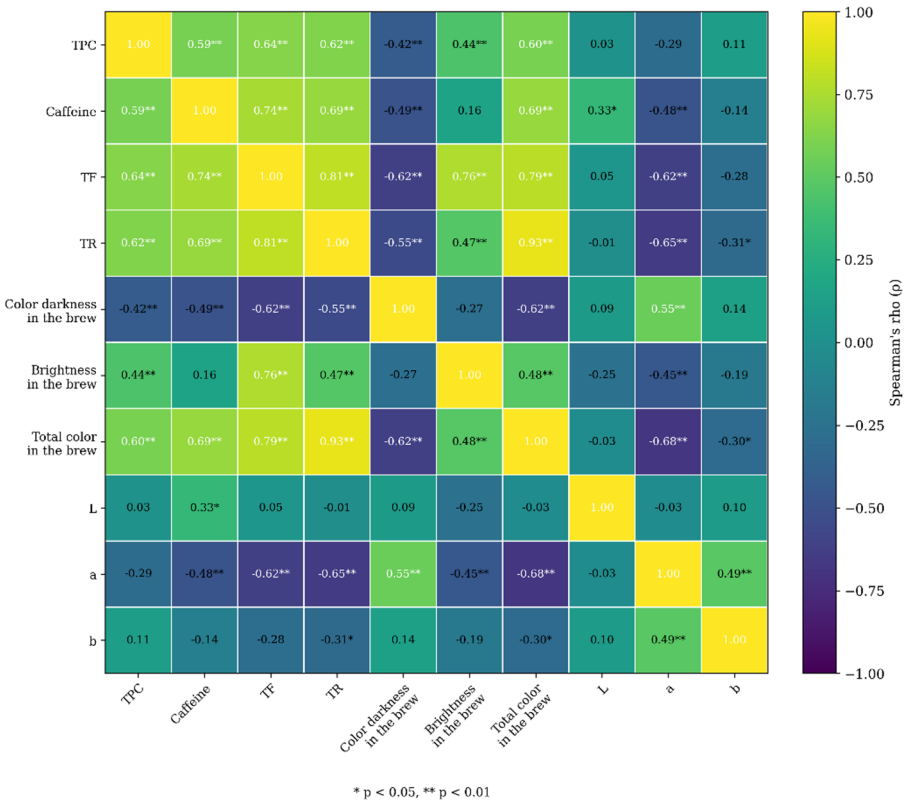


Fig. 5. Correlation relationship of chemical parameters.

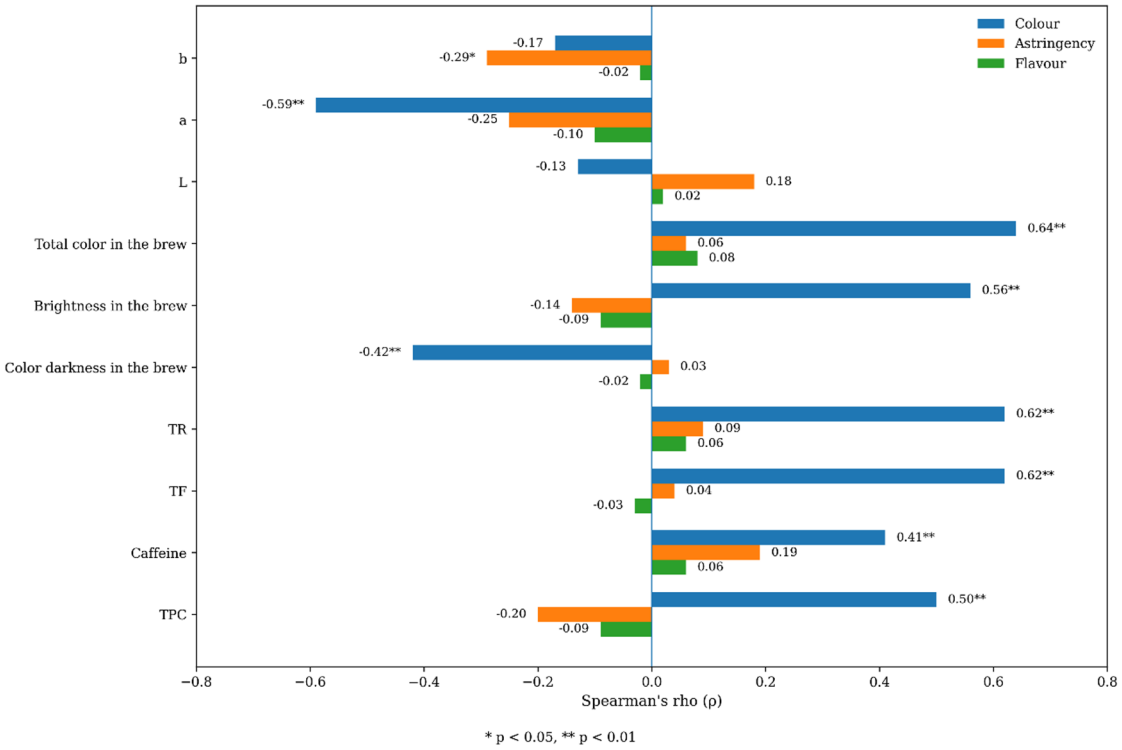


Fig. 6. Correlations between chemical and sensory parameters of black tea.

further indicated that chemical variation was reflected mainly in colour, while similarly clear relationships were not observed for astringency or flavour.

These findings help address the research gap identified in the literature by showing that sensory–chemical relationships in black tea are conditional and parameter-specific rather than uniform across all sensory traits. Chemical analyses therefore provide objective information that can complement, but not replace, trained sensory evaluation in tea quality assessment. Future studies incorporating electronic nose and electronic tongue systems could provide instrumental aroma and taste profiles to complement trained sensory evaluation and further validate sensory–chemical relationships in Turkish black tea. From a practical perspective, brewing at 95 °C and using chrome-steel teapots appear to be the most favourable conditions among those tested for enhancing sensory colour and the extraction of key chemical quality parameters. In contrast, brewing method, teapot spout condition, and extending brewing time from 15 to 20 min had more limited or parameter-specific effects, suggesting that they may be secondary factors for routine brewing standardisation.

Since the study was limited to selected commercial Turkish black tea samples and specific brewing variables as the brewing matrix, the findings should not be directly generalised to all black teas or all consumer brewing conditions. A further point that should be considered is the use of ultrapure water in the brewing trials. In the present study, ultrapure water was selected to standardise the brewing matrix and minimise the confounding effect of variation in water composition. However, this controlled condition may not fully reflect everyday tea consumption, where tap water or mineral water is commonly used. Minerals naturally present in drinking water, such as calcium, magnesium and bicarbonate, may influence the extraction of polyphenols and other soluble compounds, as well as brew colour, turbidity, astringency and overall sensory perception. Therefore, the findings should be interpreted within the context of a standardised experimental brewing system. These findings have implications for tea quality research, industry standardisation, and consumer brewing practices by linking practical brewing decisions with measurable sensory and chemical outcomes.

Data availability

All data can be requested by contacting the corresponding author, Burhan Basaran.

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References

1. Zhang, H., Qi, R. & Mine, Y. The impact of oolong and black tea polyphenols on human health. *Food Bioscience* **29**, 55–61. https://doi.org/10.1016/j.fbio.2019.03.009 (2019).
2. Başaran, B. The Importance of Tea in the Correlation between Caffeine and Health. In *Bioactive Compounds in Nutraceutical and Functional Food for Good Human Health* (IntechOpen, 2020). https://doi.org/10.5772/intechopen.93287

3. Zhao, C. N. et al. Phenolic profiles and antioxidant activities of 30 tea infusions from green, black, oolong, white, yellow and dark teas. *Antioxidants* **8** (7), 215. https://doi.org/10.3390/antiox8070215 (2019).
4. Kang, S. et al. Identification and quantification of key odorants in the world's four most famous black teas. *Food Res. Int.* **121**, 73–83. https://doi.org/10.1016/j.foodres.2019.03.009 (2019).
5. Teshome, K. Effect of tea processing methods on biochemical composition and sensory quality of black tea (Camellia sinensis (L.) O. Kuntze): A review. *J. Hortic. Forestry.* **11** (6), 84–95. https://doi.org/10.5897/JHF2019.0588 (2019).
6. Dasdemir, Y., Findik, B. T., Yildiz, H. & Birisci, E. Blueberry-added black tea: Effects of infusion temperature, drying method, fruit concentration on the iron-polyphenol complex formation, polyphenols profile, antioxidant activity, and sensory properties. *Food Chem.* **410**, 135463. https://doi.org/10.1016/j.foodchem.2023.135463 (2023).
7. Salman, S., Yılmaz, C., Gökmen, V. & Özdemir, F. Effects of fermentation time and shooting period on amino acid derivatives and free amino acid profiles of tea. *Lwt* **137**, 110481. https://doi.org/10.1016/j.lwt.2020.110481 (2021).
8. Baruah, D., Bhuyan, L. P. & Hazarika, M. Impact of moisture loss and temperature on biochemical changes during withering stage of black tea processing on four Tocklai released clones. *Two Bud.* **59** (2), 134–142 (2012).
9. Obanda, M., Owuor, P. O., Mang'oka, R. & Kavoi, M. M. Changes in thearubigin fractions and theaflavin levels due to variations in processing conditions and their influence on black tea liquor brightness and total colour. *Food Chem.* **85** (2), 163–173. https://doi.org/10.1016/S0308-8146(02)00183-8 (2004).
10. Murugesan, P., Venkateswaran, G., Sathish, G. & Shanmugaselvan, V. Enhancing the quality of naturally oxidized tea with ascorbic acid. *Int. J. Adv. Eng. Res. Sci.* **7** (4), 403–409. https://doi.org/10.22161/ijaers.74.50 (2020).
11. Samanta, T. et al. Assessing biochemical changes during standardization of fermentation time and temperature for manufacturing quality black tea. *J. Food Sci. Technol.* **52**, 2387–2393. https://doi.org/10.1007/s13197-013-1230-5 (2015).
12. Shaukat, H. et al. Tea polyphenols: Extraction techniques and its potency as a nutraceutical. *Front. Sustain. Food Syst.* **7**, 1175893. https://doi.org/10.3389/fsufs.2023.1175893 (2023).
13. Yang, C. S., Wang, H. & Sheridan, Z. P. Studies on prevention of obesity, metabolic syndrome, diabetes, cardiovascular diseases and cancer by tea. *J. Food Drug Anal.* **26** (1), 1–13. https://doi.org/10.1016/j.jfda.2017.10.010 (2018).
14. Yong, L. et al. Quantitative probabilistic assessment of caffeine intake from tea in Chinese adult consumers based on nationwide caffeine content determination and tea consumption survey. *Food Chem. Toxicol.* **165**, 113102. https://doi.org/10.1016/j.fct.2022.113102 (2022).
15. Zhang, L., Cao, Q. Q., Granato, D., Xu, Y. Q. & Ho, C. T. Association between chemistry and taste of tea: A review. *Trends Food Sci. Technol.* **101**, 139–149. https://doi.org/10.1016/j.tifs.2020.05.015 (2020).
16. Chang, M. Y. et al. Effects of infusion and storage on antioxidant activity and total phenolic content of black tea. *Appl. Sci.* **10** (8), 2685. https://doi.org/10.3390/app10082685 (2020).
17. Polat, A., Kalcıoğlu, Z. & Müezzinoğlu, N. Effect of infusion time on black tea quality, mineral content and sensory properties prepared using traditional Turkish infusion method. *Int. J. Gastron. Food Sci.* **29**, 100559. https://doi.org/10.1016/j.ijgfs.2022.100559 (2022).
18. Yu, J., Liu, Y., Zhang, S., Luo, L. & Zeng, L. Effect of brewing conditions on phytochemicals and sensory profiles of black tea infusions: A primary study on the effects of geraniol and β-ionone on taste perception of black tea infusions. *Food Chem.* **354**, 129504. https://doi.org/10.1016/j.foodchem.2021.129504 (2021).
19. Banerjee, M. B., Roy, R. B., Tudu, B., Bandyopadhyay, R. & Bhattacharyya, N. Black tea classification employing feature fusion of E-Nose and E-Tongue responses. *J. Food Eng.* **244**, 55–63. https://doi.org/10.1016/j.jfoodeng.2018.09.022 (2019).
20. Gharibzahedi, S. M. T., Barba, F. J., Zhou, J., Wang, M. & Altintas, Z. Electronic sensor technologies in monitoring quality of tea: A review. *Biosensors* **12** (5), 356. https://doi.org/10.3390/bios12050356 (2022).
21. Wang, L. et al. Evaluation of the quality grade of Congou black tea by the fusion of GC-E-Nose, E-tongue, and E-eye. *Food Chem. X* **23**, 101519. https://doi.org/10.1016/j.fochx.2024.101519 (2024).
22. Xia, H. et al. Rapid discrimination of quality grade of black tea based on near-infrared spectroscopy (NIRS), electronic nose (E-nose) and data fusion. *Food Chem.* **440**, 138242. https://doi.org/10.1016/j.foodchem.2023.138242 (2024).
23. Ramalho, S. A. et al. Effect of infusion time on phenolic compounds and caffeine content in black tea. *Food Res. Int.* **51** (1), 155–161. https://doi.org/10.1016/j.foodres.2012.11.031 (2013).
24. Salman, S., Azarabadi, N. & Ozdemir, F. Siyah çay harmaninda partikül boyutu ve demleme süresinin dem özellikleri üzerine etkisi. *Gıda* **44** (3), 442–452. https://doi.org/10.15237/gida.GD19041 (2019).
25. Food and Agriculture Organization. International tea market: Market situation, prospects and emerging issues. (2020). https://www.fao.org/3/cc0238en/cc0238en.pdf
26. Keskin, B. & Güneş, E. Social and cultural aspects of traditional drinks: A review on traditional Turkish drinks. *Int. J. Gastron. Food Sci.* **25**, 100382. https://doi.org/10.1016/j.ijgfs.2021.100382 (2021).
27. Özdemir, F., Nadeem, H. Ş., Akdoğan, A., Dinçer, C. & Topuz, A. Effect of altitude, shooting period, and tea grade on the catechins, caffeine, theaflavin, and thearubigin of Turkish black tea. *Turkish J. Agric. For.* **42** (5), 334–340. https://doi.org/10.3906/tar-1710-21 (2018).
28. George, B. & Ravola, M. Assessing the impact of SNAP-Ed: A comprehensive evaluation framework for healthy living promotion in the United States. *Agric. Rural Stud.* **2** (3), 9–9. https://doi.org/10.59978/ar02030015 (2024).
29. Bushueva, A., Adeleye, T. & Roy, P. Socioeconomic and environmental prospects of the food industry. *Agric. Rural Stud.* **2** (3), 12–12. https://doi.org/10.59978/ar02030016 (2024).
30. TS EN ISO 8586. Sensory analysis-General guidelines for the selection, training and monitoring of selected assessors and expert sensory assessors. (2014).
31. Basaran, B. et al. The levels of heavy metal, acrylamide, nitrate, nitrite, N-nitrosamine compounds in brewed black tea and health risk assessment: Türkiye. *J. Food Compos. Anal.* **120**, 105285. https://doi.org/10.1016/j.jfca.2023.105285 (2023).
32. ISO 14502-1. *Determination of Substances Characteristic of Green and Black Tea — Part 1: Content of Total Polyphenols in Tea* (Colorimetric Method Using Folin-Ciocalteu Reagent, 2005).
33. TS ISO 10727. Çay ve katı haldeki çözünebilir çay - kafein içeriğinin tayini-yüksek performanslı sıvı kromatografi yöntemi. (2004).
34. Kacar, B. *Çay ve Çay Topraklarının Kimyasal Analizleri* (Çaykur, Ankara, 1991).
35. Öğüt, Ş. T. Material culture of tea in Turkey: Transformations of design through tradition, modernity and identity. *Des. J.* **12** (3), 339–363. https://doi.org/10.2752/146069209X12530928086405 (2009).
36. Liao, Z. H. et al. Effect of teapot materials on the chemical composition of oolong tea infusions. *J. Sci. Food. Agric.* **98** (2), 751–757. https://doi.org/10.1002/jsfa.8522 (2018).
37. Lin, S. D., Yang, J. H., Hsieh, Y. J., Liu, E. H. & Mau, J. L. Effect of different brewing methods on quality of green tea. *J. Food Process. Preserv.* **38** (3), 1234–1243. https://doi.org/10.1111/jfpp.12084 (2014).
38. Pastoriza, S., Pérez-Burillo, S. & Rufián-Henares, J. Á. How brewing parameters affect the healthy profile of tea. *Curr. Opin. Food Sci.* **14**, 7–12. https://doi.org/10.1016/j.cofs.2016.12.001 (2017).
39. Zhao, M., Tang, F., Cai, W., Liu, Y. & Shan, C. Effect of brewing condition on the quality of Apocynum venetum tea. *J. Food Process. Preserv.* **46** (12), e17198. https://doi.org/10.1111/jfpp.17198 (2022).
40. Hajiaghaalipour, F., Sanusi, J. & Kanthimathi, M. S. Temperature and time of steeping affect the antioxidant properties of white, green, and black tea infusions. *J. Food Sci.* **81** (1), H246–H254. https://doi.org/10.1111/1750-3841.13149 (2016).
41. Friedman, M. et al. Distribution of catechins, theaflavins, caffeine, and theobromine in 77 teas consumed in the United States. *J. Food Sci.* **70** (9), C550–C559. https://doi.org/10.1111/j.1365-2621.2005.tb08304.x (2005).

42. Kelebek, H. LC-DAD–ESI-MS/MS characterization of phenolic constituents in Turkish black tea: Effect of infusion time and temperature. *Food Chem.* **204**, 227–238. https://doi.org/10.1016/j.foodchem.2016.02.132 (2016).
43. Almeida, T. S. D. et al. Influence of preparation procedures on the phenolic content, antioxidant and antidiabetic activities of green and black teas. *Brazilian J. Pharm. Sci.* **55**, e17695. https://doi.org/10.1590/s2175-97902019000117695 (2019).
44. Wang, K. et al. Comparison of phenolic compounds and taste of Chinese black tea. *Food Sci. Technol. Res.* **20** (3), 639–646. https://doi.org/10.3136/fstr.20.639 (2014).
45. Asil, M. H., Rabiei, B. & Ansari, R. H. Optimal fermentation time and temperature to improve biochemical composition and sensory characteristics of black tea. *Aust. J. Crop Sci.* **6** (3), 550–558 (2012).
46. Long, P., Rakariyatham, K., Ho, C. T. & Zhang, L. Thearubigins: Formation, structure, health benefit and sensory property. *Trends Food Sci. Technol.* **133** (2023), 37–48. https://doi.org/10.1016/j.tifs.2023.01.013 (2023).
47. Bhuyan, L. P., Borah, P., Sabhapondit, S., Gogoi, R. & Bhattacharyya, P. Spatial variability of theaflavins and thearubigins fractions and their impact on black tea quality. *J. Food Sci. Technol.* **52**, 7984–7993. https://doi.org/10.1007/s13197-015-1968-z (2015).
48. Ye, J. H. et al. Bitterness and astringency of tea leaves and products: Formation mechanism and reducing strategies. *Trends Food Sci. Technol.* **123**, 130–143. https://doi.org/10.1016/j.tifs.2022.02.031 (2022).
49. Zou, G., Xiao, Y., Wang, M. & Zhang, H. Detection of bitterness and astringency of green tea with different taste by electronic nose and tongue. *PLoS One* **13** (12), e0206517. https://doi.org/10.1371/journal.pone.0206517 (2018).

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JMC: Visualization; Writing-original draft; review & editing, YYA: Investigation; Methodology; Formal analysis; Visualization, AB: Formal analysis; Methodology, Visualization; Writing-original draft; review & editing, AD: Formal analysis, DÇ: Formal analysis, HEÇ: Formal analysis, AKK: Formal analysis, ŞC: Formal analysis, LM: Writing-original draft; review & editing, BB: Investigation; Methodology; Formal analysis; Software; Visualization; Writing-original draft; review & editing.

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Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

This study was conducted under the "Principles of the Declaration of Helsinki". Prior to the study, written permission was obtained from Recep Tayyip Erdogan University Research Ethics Committee [Decision No: 2024/354]. In the study, the ethical principle of 'informed consent' was fulfilled and voluntariness was taken as a basis. All information of the participants was kept in accordance with the 'confidentiality principle' throughout the study.

Additional information

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