



Assessment of the Potential Health Risks Associated with the Toxic and Essential Elements Content in Tea Samples Marketed in Türkiye

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ABSTRACT

Objectives: Tea is a widely consumed beverage that may contain both essential and toxic metals, raising nutritional and health concerns. This study evaluated the transfer of selected essential and toxic metals from black tea leaves to their infusions and assessed the associated health risks and nutritional contributions.

Materials and Methods: Black tea leaves and their infusions from eight commercially available brands sold in Türkiye were analyzed. Toxic elements [arsenic (As), aluminium, cadmium (Cd), lead (Pb)] were quantified using inductively coupled plasma mass spectrometry, while essential elements [copper, iron (Fe), magnesium (Mg), zinc] were quantified using flame atomic absorption spectrometry. Health risks were evaluated using the Estimated Daily Intake, the Target Hazard Quotient (THQ), the Hazard Index (HI), and the Incremental Lifetime Cancer Risk (ILCR).

Results: In dry tea leaves, aluminum was the predominant toxic element (12.6–25.3 mg/g), followed by Pb (21.0–39.0 µg/g); As and Cd were present at lower levels. Mg (523.0–1421.0 µg/g) and Fe (263.1–445.5 µg/g) were the most abundant essential elements. Metal concentrations in tea infusions were significantly lower than those in dry leaves ($p < 0.05$), indicating limited transfer during brewing. In infusions, aluminum (0.5–1.0 mg/g) and Mg (88.5–413.4 µg/g) were the dominant toxic and essential elements, respectively. All THQ values and the combined HI were below 1, indicating no significant non-carcinogenic risk. ILCR values for Pb were below 10^{-6} , whereas those for As ranged from 10^{-6} to 10^{-4} , indicating a moderate carcinogenic risk for As.

Conclusion: The transfer of metals from tea leaves to infusions is limited, likely due to chelation and complexation during brewing. Under typical consumption conditions, black tea infusions were within established safety limits, with risk indices below thresholds of concern. While As warrants continued monitoring, essential elements contribute only a small fraction of the recommended daily intakes. The small sample size is a limitation.

Keywords: Cancer slope factor, estimated Incremental Lifetime Cancer Risk, Hazard Index, Hazard Quotient, metal contamination

INTRODUCTION

Tea, derived from the leaves of *Camellia sinensis* L., is among the most widely consumed non-alcoholic beverages worldwide. Its popularity is attributed to its therapeutic benefits, invigorating qualities and mild stimulant effects.¹ Tea consumption has been associated with reduced serum cholesterol levels, inhibition of low-density lipoprotein oxidation and a lower risk of

cardiovascular diseases and cancer.² Tea leaves and processed tea products possess a complex chemical composition, including tannins, flavonols, alkaloids, proteins, amino acids, enzymes, aroma compounds, vitamins, minerals and essential elements.³ Tea plants are known to accumulate various metals from the soil, and numerous studies have shown that cultivation conditions can influence metal uptake in tea leaves. Metals

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such as copper (Cu), iron (Fe), zinc (Zn), and magnesium (Mg) are essential for biological functions and play critical roles in enzymatic activity, oxygen transport, and cellular metabolism. However, their health effects may vary depending on intake levels, as both deficiencies and excessive exposure can lead to adverse outcomes.¹

In contrast, arsenic (As), aluminium (Al), cadmium (Cd), and lead (Pb) are classified as non-essential elements due to their inherent toxicity, even at low concentrations. Toxic effects can also occur when the level of an essential element becomes excessively elevated, leading to harmful impacts on the central nervous system, blood constituents, and vital organs such as the lungs, liver, and kidneys, which can contribute to various disease conditions, including mental disorders.⁴ Given the importance of both essential and toxic elements in tea, numerous studies have investigated their concentrations in tea leaves and infusions.⁵⁻⁷ However, the metal content of tea may vary considerably due to environmental factors, geographic characteristics, agricultural practices, and processing conditions. Therefore, monitoring metal levels in tea products remains essential from both nutritional and toxicological perspectives.

While determining elemental concentrations and comparing them with regulatory limits is important, such an approach alone may not fully capture potential public health implications. A comprehensive human health risk assessment provides a more informative framework by integrating exposure levels with toxicological reference values. In this context, Türkiye represents a particularly relevant case, as it is among the leading countries worldwide in per capita tea consumption, with black tea constituting a major component of the daily diet across all age groups. Tea cultivation in Türkiye, particularly in the Black Sea region, is carried out under distinct regional and environmental conditions. Despite widespread consumption and potential dietary exposure to metals, data integrating both elemental composition and health risk assessment for commercially available black tea products in Türkiye remain limited.

Therefore, this study aims to assess the levels of essential and toxic elements in eight commercially available bagged black tea samples and their infusions sold in Türkiye and to evaluate the associated human health risks. Non-carcinogenic and carcinogenic risks related to toxic element exposure were assessed using the Target Hazard Quotient (THQ), Hazard Index (HI), and Incremental Lifetime Cancer Risk (ILCR). For essential elements, estimated dietary intakes were compared with established toxicological reference values, including the Tolerable Daily Intake (TDI), Provisional TDI (PMTDI), reference dose (RfD), and Tolerable Upper Intake Level (UL).

MATERIALS AND METHODS

Sample collection and preparation

The content of heavy metals and essential elements in black teas available in Turkish markets that were widely accepted and commonly consumed was analyzed in this study. A total of eight commercially available bagged black tea brands were

selected for analysis. To achieve this, black tea bags with similar production dates were sourced from the same market. The samples were stored at room temperature, kept away from direct sunlight, and were confirmed to be undamaged prior to analysis.

Analytical procedures

For metal determination, 0.1 g of each dry tea sample was placed in a Teflon vessel and digested in a microwave-assisted acid digestion system (Anton Paar, Germany). The digestion process utilized 4.5 mL of 20% nitric acid (Merck, Germany) and 0.5 mL of hydrogen peroxide (Sigma, Germany).

For tea infusions, three black tea bags (weighing approximately 6 g in total) from each sample were steeped in 200 mL of distilled water at room temperature for 5 minutes according to brewing guidelines recommended by the tea industry. This standardized brewing duration was selected to ensure comparability between samples and to represent realistic exposure conditions for routine tea consumption.⁸ During this time, the mixture was stirred at 400 rpm using a magnetic stirrer. After brewing, the tea bags were held above the beaker for 1 minute to allow excess liquid to drain. The resulting infusion was capped and stored in a refrigerator until analysis. No additional preparation was required for the infusion samples prior to measurement.

Elemental analysis was performed using a validated, in-house accredited method. Toxic elements (As, Al, Cd, Pb) were quantified using Inductively Coupled Plasma Mass Spectrometry (Thermo Scientific ICAP Q Series, Germany),⁹ while essential elements (Cu, Fe, Mg, Zn) were determined using Flame Atomic Absorption Spectrometry (Analytik Jena, Germany).¹⁰

Risk assessment for consumers

The Estimated Daily Intake (EDI) of toxic elements from tea infusion samples was determined using the equation:

$$EDI = [\text{concentration} \times \text{ingestion rate (IR)} \times \text{exposure frequency (EF)} \times \text{exposure duration (ED)}] / [\text{body weight (BW)} \times \text{averaging time}]$$

Where EDI is the EDI (mg/kg/day), C is the metal concentration in tea infusion samples and IR is the daily consumption of tea per capita in Türkiye (10 g/day). EF is the EF (365 day/year), ED is the ED for adults (54 years), BW is the average BW of consumers (60 kg) and AT indicates the average lifetime (70 years × 365 days).^{9,11} In the risk assessment, per-capita daily tea consumption was assumed to be 10 g/day (dry weight), a conservative estimate for a high-tea-consuming population such as Türkiye. Türkiye has one of the highest per capita tea consumption rates in the world, with annual average consumption exceeding 3.2 kg per person, corresponding to an average of several cups of tea per day.¹²

To assess potential non-carcinogenic health risks, the THQ was calculated for each toxic element (THQ = EDI/RfD). RfD is the oral RfD for the intended trace element (As = 0.0003, Al = 1, Pb = 0.002 mg/kg/day).¹³ If the THQ value is less than one, it

indicates no significant risk of non-carcinogenic adverse health effects to consumers. Additionally, to evaluate the potential cumulative hazard resulting from exposure to multiple metal, HI was calculated ($HI = THQ_{As} + THQ_{Pb} + THQ_{Cd} + THQ_{Al}$).

Cancer risk was estimated as the lifetime probability of developing cancer due to exposure to potential carcinogens. The ILCR was calculated as the product of the EDI and the cancer slope factor (CSF), the latter being derived from the dose-response curve for ingestion of the toxicant, according to the formula:

$$ILCR = EDI \times CSF^{14}$$

For essential elements, the risk assessment compared the EDI of Zn, Fe, Cu, and Mg from black tea consumption with established toxicological safety guidelines, including the TDI, PMTDI, RfD, and UL.

Statistical analysis

All analyses were conducted using SPSS software version 21.0. The concentrations of toxic and essential elements were expressed as mean $\pm$ standard deviation. One-way analysis of variance, followed by Tukey's post-hoc HSD test, was used to determine significant differences between the mean concentrations in dry tea leaves and tea infusions. A *p*-value of <0.05 was considered statistically significant.

RESULTS

Metal concentrations in tea leaves and tea infusions

In this study, eight different black tea bag samples, representing the most frequently consumed brands in Türkiye, were selected for analysis. The toxic and essential element contents per tea bag sample are presented in Table 1.

The levels of both toxic and essential elements were roughly similar among the tested brands. The most abundant toxic metals in tea leaves were Al (12.6–25.3 mg/g) and Pb (21.0–39.0 µg/g), whereas the most prevalent essential elements were Mg (523.0–1421.0 µg/g) and Fe (263.1–445.5 µg/g). The contents of

Cu, Zn, As, and Cd were in the ranges of 25.0–29.3 µg/g, 37.2–51.3 µg/g, 0.7–1.6 µg/g, and 0.6–2.1 µg/g, respectively.

Toxic and essential elements were also measured in tea infusions prepared following the recommended steeping time of 5 minutes for black tea. The concentrations in infusion samples for each brand are shown in Table 2; Figure 1 compares the average element concentrations in dry tea leaves and in the corresponding infusions.

As shown in Table 2, the primary toxic metal found in the infusion samples was Al, with concentrations ranging from 0.5 to 1.0 mg/g. On the other hand, the predominant essential element was Mg, with concentrations ranging from 88.5 to 413.4 µg/g. The total contents of other elements determined in tea infusions are presented in the following order: Fe (39.4 to 70.0 µg/g), Cu (13.5 to 17.8 µg/g), Zn (9.4 to 16.9 µg/g), As (0.1 to 0.3 µg/g), and Pb (0.1 to 0.5 µg/g). The concentrations of Cd in the infusion samples were below the limit of detection of the available analytical technique (3.7 ppb).

All elements showed a significant decrease ($p < 0.05$) in infusions compared with those in dry leaves. The extraction efficiency of each element was calculated as the concentration of the element in tea infusions divided by its total concentration in black tea leaves (Figure 1).

Health risk assessment

Table 3 presents the EDI, THQ, and HI values calculated for the non-carcinogenic risk assessment of tea infusions. The EDI was the highest for Al among all brands under investigation, while it was relatively similar for As and Pb. The lowest THQ was observed for Pb, while As and Al exhibited similar THQ values, both higher than that for Pb. None of the individual THQs for Al, As, and Cd exceed the value of 1 in any of the tea infusion samples examined. This observation implies that the consumption of the analyzed tea infusions does not pose a significant risk of non-carcinogenic health effects. The HI, which accounts for the combined impact of consuming multiple toxic elements, also remains below 1 (Table 3). The obtained values indicate that Al contributes the most to the

Table 1. Toxic and essential element level in tea leaves in tea bag samples (mean + standard deviation).

Sample	Toxic elements level				Essential elements level			
	As (µg/g)	Al (mg/g)	Cd (µg/g)	Pb (µg/g)	Zn (µg/g)	Fe (µg/g)	Cu (µg/g)	Mg (µg/g)
Brand A	1.0 $\pm$ 0.1	18.1 $\pm$ 0.9	1.0 $\pm$ 0.1	21.0 $\pm$ 1.1	37.2 $\pm$ 1.4	263.1 $\pm$ 5.0	25.0 $\pm$ 0.7	523.0 $\pm$ 35.4
Brand B	1.0 $\pm$ 0.1	17.5 $\pm$ 0.9	0.9 $\pm$ 0.0	21.0 $\pm$ 1.1	42.6 $\pm$ 0.8	350.4 $\pm$ 14.0	28.5 $\pm$ 0.8	1134.2 $\pm$ 53.0
Brand C	1.6 $\pm$ 0.0	25.2 $\pm$ 1.3	1.0 $\pm$ 0.1	26.0 $\pm$ 1.3	48.6 $\pm$ 0.8	445.5 $\pm$ 5.1	28.7 $\pm$ 1.6	1421.0 $\pm$ 33.5
Brand D	1.6 $\pm$ 0.1	25.3 $\pm$ 1.3	1.2 $\pm$ 0.1	28.0 $\pm$ 1.4	47.7 $\pm$ 6.0	416.7 $\pm$ 7.0	27.8 $\pm$ 1.7	952.0 $\pm$ 30.3
Brand E	1.5 $\pm$ 0.1	23.3 $\pm$ 1.2	2.1 $\pm$ 0.1	25.0 $\pm$ 1.3	51.3 $\pm$ 6.1	417.6 $\pm$ 20.7	27.7 $\pm$ 0.9	1049.3 $\pm$ 49.5
Brand F	0.7 $\pm$ 0.0	12.6 $\pm$ 0.6	0.9 $\pm$ 0.0	21.0 $\pm$ 1.1	48.9 $\pm$ 6.4	360.9 $\pm$ 9.6	29.3 $\pm$ 0.6	1161.0 $\pm$ 24.3
Brand G	0.7 $\pm$ 0.1	13.1 $\pm$ 0.7	0.6 $\pm$ 0.0	21.0 $\pm$ 1.1	44.4 $\pm$ 1.4	330.3 $\pm$ 12.8	29.1 $\pm$ 0.9	1263.2 $\pm$ 33.0
Brand H	1.3 $\pm$ 0.1	27.0 $\pm$ 1.3	1.3 $\pm$ 0.1	39.0 $\pm$ 2.0	40.8 $\pm$ 5.4	400.5 $\pm$ 9.9	27.7 $\pm$ 1.0	937.0 $\pm$ 36.5

Al, aluminium; As, arsenic; Cd, cadmium; Cu, copper; Fe, iron; Mg, magnesium; Pb, lead; Zn, zinc.

Table 2. Toxic and essential elements level in tea infusion samples (mean $\pm$ standard deviation).

Sample	Toxic elements level				Essential elements level			
	As ($\mu\text{g/g}$)	Al (mg/g)	Cd ($\mu\text{g/g}$)	Pb ($\mu\text{g/g}$)	Zn ($\mu\text{g/g}$)	Fe ($\mu\text{g/g}$)	Cu ($\mu\text{g/g}$)	Mg ($\mu\text{g/g}$)
Brand A	0.3 ± 0.01	0.9 ± 0.04	<LOD	0.1 ± 0.01	9.4 ± 0.35	39.4 ± 2.20	17.2 ± 0.49	209.8 ± 13.61
Brand B	0.3 ± 0.03	0.7 ± 0.04	<LOD	0.3 ± 0.02	11.4 ± 0.14	52.3 ± 0.13	17.7 ± 0.50	292.0 ± 19.26
Brand C	0.2 ± 0.01	0.8 ± 0.04	<LOD	0.1 ± 0.01	12.8 ± 0.71	55.8 ± 1.17	16.5 ± 0.49	124.0 ± 15.76
Brand D	0.2 ± 0.01	0.8 ± 0.04	<LOD	0.2 ± 0.01	14.2 ± 1.06	65.4 ± 0.10	17.5 ± 0.45	88.5 ± 13.78
Brand E	0.2 ± 0.01	0.8 ± 0.04	<LOD	0.4 ± 0.02	13.6 ± 1.32	70.0 ± 1.47	17.8 ± 0.90	136.5 ± 18.02
Brand F	0.1 ± 0.01	0.5 ± 0.03	<LOD	0.5 ± 0.02	14.4 ± 1.12	61.3 ± 0.49	15.0 ± 0.69	280.4 ± 11.89
Brand G	0.1 ± 0.01	0.7 ± 0.04	<LOD	0.5 ± 0.02	16.9 ± 1.02	67.2 ± 1.79	13.5 ± 0.46	413.4 ± 7.86
Brand H	0.1 ± 0.01	1.0 ± 0.05	<LOD	0.2 ± 0.01	13.1 ± 1.06	67.7 ± 5.09	13.7 ± 0.32	92.1 ± 7.10

Al, aluminium; As, arsenic; Cd, cadmium; Cu, copper; Fe, iron; LOD, limit of detection; Mg, magnesium; Pb, lead; Zn, zinc.

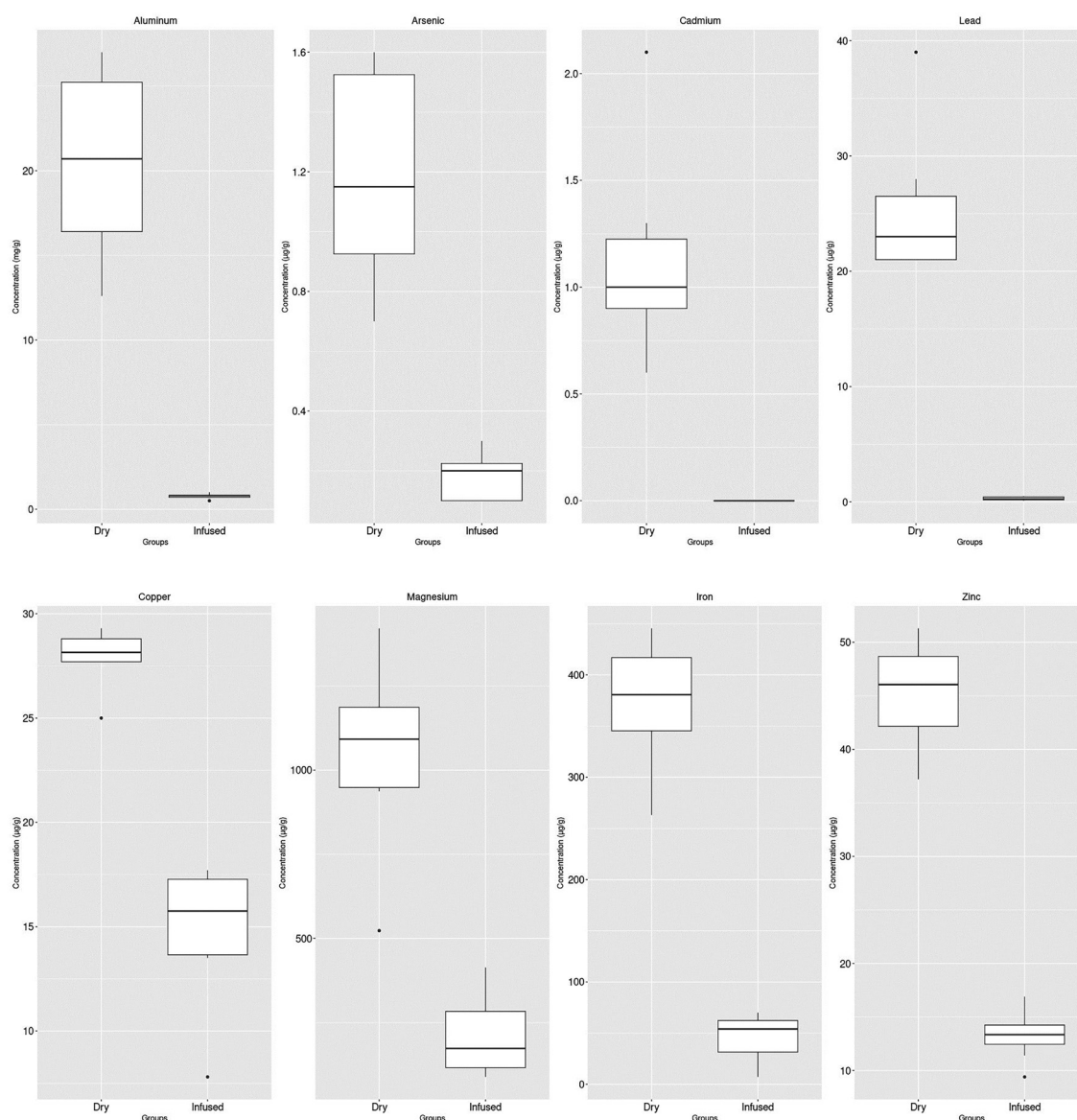


Figure 1. The comparison of toxic and essential elements content in dry leaves and infusions of black tea.

HI of the examined tea infusion samples, at 50%. As contributes 41% and Pb contributes 9% (Figure 2). The carcinogenic risk of As and Pb via the consumption of tea infusions was evaluated and is summarized in Table 4. The assessment was based on the CSF values for inorganic As (1.5 per mg/kg/day) and Pb (0.0085 mg/kg/day). An ILCR above 10^{-4} indicates high risk, while values below 10^{-6} indicate minimal risk; values between 10^{-6} and 10^{-4} indicate moderate risk. In this study, ILCR values for Pb were below 10^{-6} in all tea infusion samples, indicating negligible carcinogenic risk. ILCR values for As ranged from 10^{-6} to 10^{-4} , indicating a moderate risk.

For the essential elements, the EDI of Fe, Cu, Zn, and Mg from tea infusions was compared with their toxicological reference values (PMTDI, TDI, UL, or RfD) as presented in Table 5. The results indicated that the average EDI for these elements constituted a very small fraction (0.01%–5%) of the established reference values for a 60-kg person. Therefore, the intake of these essential elements through tea infusions is unlikely to pose any significant health risk to the average consumer.

DISCUSSION

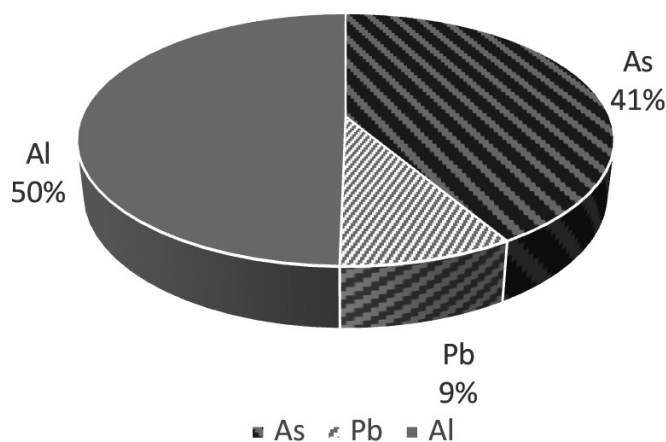


Figure 2. Average percentage contribution of Al, As and Pb to the HI. Al, aluminium; As, arsenic; HI, Hazard Index; Pb, lead.

Previous studies have reported varying concentrations of toxic and essential elements in black tea from different regions. Matsuura et al.⁶ reported an average Al level of 0.8 mg/g in black tea bags commercially available in Japan. Tang et al.¹⁵ determined Al concentration of 0.48 mg/g in dry tea leaves marketed in Hangzhou, China. In another study, the ranges of Al and Pb in mature tea leaves from Puan County, China were found to be 4.3–10.4 mg/g and 0.56–1.26 µg/g, respectively.¹⁶ Ghale-Askari et al.¹⁷ reported the mean concentrations of 1.96, 0.048, 2.195 and 0.03 µg/g for Pb, As, Al, and Cd in the tea leave samples marketed in Neishabour city, Iran. In another study the Pb, Cd, As and Cu concentrations in the Sri Lankan and Indian black tea were 0.14, 0.017, 0.057, 11.29 mg/kg, and 0.21, 0.02, 0.067, 14.56 mg/kg, respectively.¹⁸ The quality of tea brands available in the retail market in Saudi Arabia were evaluated based on their metal contents in the study conducted by Al-Oud.¹⁹ The concentrations of the toxic elements Pb and Cd in tea leaves were 0.03–14.84 µg/g and below the detectable limit of 0.37 µg/g, respectively. Among essential elements, Fe was the most abundant (326–1155 µg/g), followed by Zn (26.7–53.9 µg/g) and Cu (22.1–40.7 µg/g). More recently, Rahmani et al.²⁰ reported that imported black teas in Mashhad, Iran contained concentrations ranging from 6.81 to 35.21 µg/g for Cu, 14.61 to 164.84 µg/g for Zn, 0.038 to 1.62 µg/g for Pb and 0.006 to 0.19 µg/g for Cd.

Overall, our findings for the toxic element content of dry tea leaves were higher than those reported in previous studies. The highest level of Al among previous studies was found in the samples obtained from factories located in Giresun, Trabzon and Rize in Türkiye.²¹ The average Al content of the tea was found to be between 8.9 and 14.1 mg/g in Rize, between 8.2 and 11.2 mg/g in Trabzon, and between 8.8 and 15.7 mg/g in Giresun.

The elevated concentrations of toxic elements in tea samples from Türkiye are likely attributable to specific cultivation conditions and environmental factors, including soil characteristics, climate, altitude, and rainfall. Previous studies have indicated that significant quantities of metals may translocate from the soil to tea leaves.²² In particular, tea

Table 3. EDI, THQ and HI values of the studied toxic elements in tea infusions.

Sample	EDI/THQ				
	As	Al	Cd*	Pb	HI
Brand A	3.7E-05/0.12	1.2E-01/0.12	NA	1.7E-05/0.01	0.25
Brand B	3.5E-05/0.12	9.02E-02/0.09	NA	4.3E-05/0.02	0.23
Brand C	3.0E-05/0.10	1.1E-01/0.11	NA	1.7E-05/0.01	0.21
Brand D	2.4E-05/0.08	1.0E-01/0.10	NA	2.1E-05/0.01	0.19
Brand E	2.2E-05/0.07	9.8E-02/0.10	NA	4.3E-05/0.02	0.19
Brand F	2.1E-05/0.07	7.4E-02/0.087	NA	6.4-05/0.03	0.17
Brand G	1.9E-05/0.06	9.6E-02/0.10	NA	6.0E-05/0.03	0.19
Brand H	1.7E-05/0.06	1.3E-01/0.13	NA	2.6E-05/0.01	0.20

*The risk assessment for Cd was not conducted because its concentration was found to be below the limit of detection in all investigated infusion samples. Al, aluminium; As, arsenic; Cd, cadmium; EDI, Estimated Daily Intake; HI, Hazard Index; NA, not applicable; THQ, Target Hazard Quotient.

leaves grown in acidic soils tend to accumulate higher levels of metals, a phenomenon linked to the soil's acidic properties.²³ Özyazıcı et al.²⁴ further corroborated this by reporting the acidic pH range (3.14–6.39) of soils in regions of Türkiye where tea cultivation is prevalent.

It is crucial to emphasize that the retention of elements within an organism depends on two factors: the overall element content within tea leaves and the fraction that is extracted into the infusion.²⁵ Therefore, in this study, levels of both toxic and essential elements in tea infusions were analyzed following the recommended 5-minute steeping time for black tea. It has been acknowledged that the quantity of elements extracted into the tea infusions primarily depends on whether the compound is tightly bound to the matrix or more soluble in the employed solution.²⁶ Hence, the amount of minerals in tea infusions is determined by the extraction efficiencies and the total concentration of metals within the tea leaves.²⁵

According to their extraction efficiencies, elements are classified into highly (>55%), moderately (22–55%) and poorly extractable elements (<20%).²⁷ In this study, after 5 minutes of brewing, the derived extraction efficiencies for the elements under investigation indicated that As, Al, Cd, Pb, Fe, and Mg were poorly extractable. Zn is in the moderately extractable range, whereas Cu is in the highly extractable range. Similarly, in a study conducted by Salahinejad and

Aflaki²⁵ on black tea samples from the Iranian market, Cd, Pb and Fe were categorized as poorly extractable, while Zn fell into the moderately extractable category. In contrast to our results, Al and Mg were classified as moderately extractable, and Cu was categorized as poorly extractable in that study. The discrepancy in findings between the two studies may be attributable to the longer brewing period (30 minutes) used in the other study, compared with the shorter period (5 minutes) used in our investigation. In the present study, Al exhibited the highest EDI among the investigated elements, while As and Pb showed comparable EDI values. Conversely, Pb had the lowest THQ, whereas Al and As displayed similar and relatively higher THQ values. In order to calculate the EDI and THQ, an established oral RfD is essential. The RfD is an estimate of the daily intake of a substance, considered safe for the general population, including sensitive groups, over a lifetime without causing adverse health effects. The RfD is derived from studies identifying the No Observed Adverse Effect Level, the Lowest Observed Adverse Effect Level, or the benchmark dose, with safety factors applied to address uncertainties in the available data.²⁸

Al has an oral RfD of 1 mg/kg/day. Dietary sources account for over 90% of non-occupational human exposure to aluminum.¹³ Experimental animal studies have reported potential neurotoxic effects associated with prolonged exposure to Al. Growing scientific evidence suggests a potential connection between aluminum's neurotoxic effects and the onset of Alzheimer's disease. Although this association remains primarily correlational, aluminum has also been implicated in age-related cognitive decline and in neurodegenerative disorders such as Parkinson's disease. Research in humans has predominantly focused on dialysis patients, especially those suffering from dialysis encephalopathy, to explore the impact of aluminum exposure on brain function.²⁹

The established oral RfD for inorganic As is 0.0003 mg/kg/day. Similar to Al, the primary source of As for individuals not exposed through occupational settings is their diet. Seafood commonly carries elevated levels of As, primarily in the form of the less harmful organic As species.¹³ Aside from food, beverages such as tea may be significant sources of dietary exposure to toxic elements in daily life. The Food and Agriculture Organization (FAO) of the United Nations/World Health Organization (WHO) has established a provisional tolerable weekly intake (PTWI)

Table 4. The ILCR for As and Pb was analysed in tea infusions.

Sample	ILCR*	
	As	Pb
Brand A	5.5E-05	1.5E-07
Brand B	5.3E-05	3.6E-07
Brand C	4.4E-05	1.5E-07
Brand D	3.6E-05	1.8E-07
Brand E	3.2E-05	3.6E-07
Brand F	3.1E-05	5.5E-07
Brand G	2.9E-05	5.1E-07

*ILCR was calculated by multiplying the EDI by the CSF. Oral CSF for inorganic As and Pb is 1.5 and 8.5 x 10⁻³ mg/kg/day, respectively.²⁶ As, arsenic; CSF, cancer slope factor; EDI, Estimated Daily Intake; ILCR, Incremental Lifetime Cancer Risk; Pb, lead.

Table 5. Comparison of the EDI of Zn, Fe, Cu and Mg through 10 g tea infusion/day consumption and toxicological parameters.

	Toxicity reference value (mg/day)					Percentage of considered parameters according to EDI			
	PMTDI	RfD	TDI	UL	Average EDI (mg/day)	PMTDI	RfD	TDI	UL
Zn	1		10	40	0.002	0.20		0.02	0.01
Fe	0.8			45	0.008	1.00			0.02
Cu	0.5	0.04		10	0.002	0.40	5.00		0.02
Mg				350	0.026				0.01

Cu, copper; EDI, Estimated Daily Intake; Fe, iron; Mg, magnesium; PMTDI, Provisional TDI; RfD, reference dose; TDI, Tolerable Daily Intake; UL, Tolerable Upper Intake Level; Zn, zinc.

for As, with an estimated maximum limit of 15 µg/kg of BW (equivalent to 900 µg per person; Karak and Bhagat¹). According to Yuan et al.,³⁰ the consumption of 10 g of Chinese tea per person daily results in a maximum inorganic As contribution of 2.26 µg from tea infusion. This equates to 0.038 µg/kg/day, excluding the contribution from water. This value reported in that study corresponds to only 1.8% of the recommended PTWI of 2.1 µg per kg of BW per day, as established by the FAO/WHO. In the present study, the consumption of infusions from tea samples in the Turkish market at an IR of 10 g Pbs to an inorganic As intake of 0.025 µg/kg/day. This corresponds to a PTWI that is slightly lower (by 1.2%) than that reported in the study conducted in China.

Exposure to Pb in children continues to be a significant health concern due to the neurological effects that persist from prolonged exposure to relatively low levels of Pb.³¹ As a result, numerous countries have established permissible limits for Pb in foods and beverages, acknowledging that these are significant sources of Pb accumulation in the human body. The permissible limit of Pb for food and beverages in Europe is 5 mg/kg¹. As indicated in Table 1, the concentration of Pb in all investigated tea leaf samples exceeded the limit of 5 mg/kg. However, the levels of Pb in tea infusions were found to be significantly below this limit. None of the individual THQs for Al, As, or Cd exceeded 1, indicating that consumption of the analyzed tea infusions is unlikely to pose significant non-carcinogenic health risks. The HI also remained below 1, suggesting that combined exposure to multiple toxic elements does not result in cumulative adverse effects. Al contributed the largest proportion of the HI, followed by As and Pb, reflecting their relative impact on total risk.

Potential carcinogenic risks from As and Pb exposure through tea consumption were also evaluated in this study. The carcinogenic risk assessment was based on the CSF values for inorganic As (1.5 per mg/kg/day) and Pb (0.0085 mg/kg/day). The CSF is a key toxicity metric that quantifies the relationship between dose and response. ILCR above 10^{-4} suggests a high cancer risk, while an ILCR below 10^{-6} indicates minimal risk. Values falling between 10^{-6} and 10^{-4} denote moderate risk.^{9,28} In this study, the ILCR for Pb in all tea infusion samples was below the safe threshold of 10^{-6} , indicating no significant cancer risk. For As, ILCR values ranged from 10^{-6} to 10^{-4} across all samples, indicating a moderate carcinogenic risk. However, the As concentrations measured in this study represent total As, not solely inorganic As. Therefore, the carcinogenic risk might be overestimated because not all As in the samples is present as inorganic species.

For essential elements, the EDI of Fe, Cu, Zn, and Mg from tea infusions was compared to their toxicological reference values, including PMTDI, TDI, UL, or RfD.³²

Tea is one of the most widely consumed beverages worldwide and represents an important component of a balanced diet. However, tea consumption may also contribute to dietary exposure to both essential and toxic elements because tea plants naturally accumulate them. The analysis of infusions from eight commercially available tea brands indicated that there were no

significant non-carcinogenic health risks associated with Al, As, Cd, and Pb, either individually or cumulatively, as reflected by the HI. Although a moderate carcinogenic risk was observed for As, this assessment was based on total As concentrations and may therefore overestimate the actual risk associated with inorganic As.

Continuous monitoring of levels of both toxic and essential elements in foods and beverages remains crucial for quality control and food safety. The findings of this study provide useful data to support ongoing efforts aimed at improving the safety and quality of black tea products in the region.

Study limitations

A limitation of the present study is the relatively small number of tea brands analyzed ($n = 8$), which may limit statistical power and the generalizability of the findings. Although the selected samples represent some of the most widely consumed black tea products available in the Turkish market, the results should be interpreted with caution and may not fully reflect the variability of all black tea brands and production batches. Future studies that include a larger number of samples from different production origins would be valuable for further refining population-level exposure assessments.

In addition, polyphenols, such as tannins in tea, can chelate metal ions, and divalent metals often form insoluble complexes, both of which can significantly reduce metal bioavailability. However, data on the potential absorption of tannin-metal complexes in tea drinkers are scarce in the literature. Therefore, simply listing metal concentrations is insufficient for a comprehensive risk assessment.

Another limitation of this study is that metal extraction was evaluated at a single brewing time (5 minutes). Although this duration reflects standard preparation practices, variations in brewing time, water temperature, or repeated infusions may influence metal extraction rates. Therefore, the results may not fully represent individual consumption habits, and future studies that assess different brewing conditions would provide a more comprehensive exposure assessment.

CONCLUSION

This study provides an in-depth analysis of the concentrations of essential and toxic elements in black tea bag samples from Türkiye, offering valuable insights into their potential health implications. The findings indicate that both essential and toxic elements are present in varying concentrations in the tea leaves and their infusions. Among the toxic elements, Al and Pb were the most abundant in dry tea leaves, with Al also being the predominant toxic element in tea infusions. Essential elements such as Mg, Fe, Cu, and Zn were also detected, with Mg being the most prevalent.

The health risk assessments (EDI, THQ, and HI) revealed that the levels of individual toxic elements in tea infusions and their cumulative non-carcinogenic risks are within acceptable limits. The carcinogenic risk assessment highlighted a moderate risk for as; however, this is likely overestimated because total,

rather than inorganic, As was measured. Importantly, the essential elements were present at concentrations significantly below their toxicological thresholds, indicating no risk of adverse health effects from consumption of tea infusions. The study underscores the influence of environmental factors, soil characteristics, and agricultural practices on the accumulation of elements in tea plants. It also highlights the importance of extraction efficiencies in determining the transfer of these elements from tea leaves to infusions, with most elements categorized as poorly or moderately extractable under standard brewing conditions.

Ethics

Ethics Committee Approval: Ethical approval is not required for this study.

Informed Consent: Informed consent is not required.

Footnotes

Authorship Contributions

Concept: M.H., M.Ş., G.E., S.H., A.A., Design: M.H., M.Ş., G.E., S.H., A.A., Data Collection or Processing: M.H., M.Ş., G.E., S.H., A.A., Analysis or Interpretation: M.H., M.Ş., G.E., S.H., A.A., Literature Search: M.H., M.Ş., G.E., S.H., A.A., Writing: M.H., M.Ş., G.E., S.H., A.A.

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