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Essential and Non-Essential Elements Analysis in Black Teas and their Extraction Efficiency using Neutron Activation Analysis

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This study aims to evaluate the concentrations of essential (Na, K, Mg, Fe, Zn, Co, Mn, Cr) and non-essential (Al, Ba, Rb, Br, La, Sc, Sm) elements in black tea leaves and their infusions. Additionally, it investigates the extraction efficiency of these elements to assess their dietary contributions, particularly for populations of Iran with high tea consumption. Neutron activation analysis (NAA) was employed to determine elemental concentrations in five popular black teas commonly consumed in Iran. The analysis quantified the transfer of elements from dry tea leaves to tea infusions, calculating extraction efficiencies to assess their potential dietary relevance. Elements with high extraction efficiency (>55%) included Rb (79.3%), K (78.7%), Br (65.9%) and Cr (61.3%). Moderate extraction efficiencies (20-55%) were observed for Co (32.4%) and La (20.6%), while poor extraction efficiencies (<20%) were noted for Mg, Ba, Zn, Sm, Na, Al and Sc. Black tea was identified as a dietary source of trace elements such as Cr, Rb and Co, highlighting its potential nutritional value for high-consumption populations. This study provides novel insights into the elemental composition and extraction efficiency of black tea, emphasizing its role as a dietary source of essential and trace elements. The findings have significant implications for understanding the nutritional contributions of tea in regions with high consumption, particularly in Iran, where tea is a staple beverage.

Keywords: Black tea, Neutron activation analysis, Extraction efficiency, Essential and non-essential elements, Daily dietary intake.

INTRODUCTION

Tea, derived from *Camellia sinensis*, is the most widely consumed beverage globally, second only to water, with an estimated 20 billion cups enjoyed daily [1,2]. In Iran, tea plays a significant role in daily life, with an average person consuming approximately 1243 mL or 5 to 6 cups per day, placing the country among the highest tea-consuming nations [3,4]. This high consumption rate underscores tea's potential as a source of both essential nutrients and non-essential or toxic elements, highlighting the importance of understanding its mineral profile and health implications for Iranian consumers.

The mineral content of tea is influenced by various factors, including soil composition, agricultural practices and processing techniques [5-9]. Black tea leaves are rich in essential minerals, such as potassium (K), magnesium (Mg), calcium (Ca) and manganese (Mn), which contribute to tea's health-promoting properties, such as antioxidative effects, cancer prevention and immune support [10-12]. However, tea may also contain potentially toxic elements like aluminum (Al), cadmium (Cd) and lead (Pb), which pose health risks when present in high amounts [13,14].

Numerous studies have demonstrated that the transfer of elements from tea leaves to infusions can vary widely, influenced by factors like infusion time, temperature and brewing method [15]. The degree of extraction of elements from leaves to infusion determines the bioavailability of essential minerals, as well as the potential exposure to harmful elements, underscoring the need to evaluate the levels of both beneficial and toxic elements in tea infusions. Analytical methods such as neutron activation analysis (NAA), inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) have been commonly used to determine the elemental profile of tea [4,16,17]. Among these, NAA is particularly valuable for tea analysis due to its non-destructive nature and ability to detect a broad spectrum of elements with high precision [18].

Despite the significance of black tea in Iranian culture, limited research has investigated the comprehensive elemental composition of black tea brands available in Iran, especially for less frequently studied elements like barium (Ba), cobalt (Co), rubidium (Rb), lanthanum (La), scandium (Sc) and samarium (Sm) [3,4,16]. Considering Iran's significant consumption levels, it is vital to understand the levels of both essential and non-essential elements in black tea, as well as their migration into tea infusions, to evaluate possible health impacts.

This study addresses a research gap by analyzing the elemental content of several popular black tea brands widely consumed in Iran. Using neutron activation analysis (NAA) technique, it provides a comprehensive assessment of essential and non-essential element concentrations in tea leaves and their extraction efficiencies into infusions. This analysis offers valuable insights into the estimated daily intake of each element, highlighting both the nutritional benefits and potential health risks of regular tea consumption. Furthermore, the study examines the variability in elemental profiles across different brands, including both domestic and imported varieties, to evaluate the safety and quality of tea available to consumers in Iran.

EXPERIMENTAL

Black tea sample preparation and processing: Five types of commercial black teas, commonly consumed in Iran, were purchased from the local markets in Tehran, Iran. These teas included two Iranian brands, Noor Jafari and Bahar Lahijan, sourced from the Gilan province in northern Iran and three imported brands: Shahrzad (India), Ahmad (Ceylon) and Golestan (Ceylon), both imported from Sri Lanka.

To prepare the samples for the neutron activation analysis, the dry tea leaves were crushed, ground and sieved through a 125 µm mesh to ensure uniform particle size. The powdered tea samples were then dried at 85 ºC for 24 h to remove any moisture.

Infusion preparation: The tea infusions were prepared using a traditional brewing method commonly practiced in Iran. For each infusion, 5 g of dry tea leaves were added to 500 mL of boiled distilled water in a steel kettle. The water temperature was maintained at approximately 95 ºC and the tea was allowed to steep for 10 min. Following the infusion period, the tea solution was filtered to separate the tea dregs from the liquid. The tea dregs in order to neutron activation analysis, were dried, ground into a fine powder and homogenized, then dried at 85 ºC for 24 h.

The chosen tea-to-water ratio and brewing duration were based on standard tea consumption practices in Iran, where the average person consumes approximately 4.4 g of black tea leaves daily [4]. Since North Iranian teas generally require a higher leaf mass for optimal flavour, 5 g were used for all samples to maintain consistency across brands.

Determination of elemental concentrations in tea samples: Instrumental neutron activation analysis (NAA) was employed to determine the elemental concentrations. This technique converts elements in the samples into radioactive isotopes by neutron irradiation. Upon decay, these isotopes emit γ-rays with specific energies, allowing for the identification of isotopic composition and quantification of elements.

Using the comparative method of NAA, both the unknown sample and a standard were irradiated simultaneously. The activated samples were then counted at identical positions relative to the high-purity germanium (HPGe) detector and their spectra were recorded using Gamma Vision software. Concentrations were calculated by comparing the recorded spectra of the samples to those of the standards. The specific equation for concentration determination [19] is as follows:

$$\frac{A_{sam}}{A_{std}} = \frac{m_{sam}(e^{-\lambda T_d})_{sam}}{m_{std}(e^{-\lambda T_d})_{std}} \quad (1)$$

where A represents activity, m is the element mass, λ the decay constant and T_d is the decay time.

The calculation was further refined as:

$$C_{sam} = C_{std} \times \frac{w_{std}}{w_{sam}} \times \frac{e^{-\lambda t_{d(std)}}}{e^{-\lambda t_{d(sam)}}} \times \frac{N^{sam}}{N^{std}} \quad (2)$$

where C is the concentration, w is the sample weight and N the net area under the radionuclide's gamma energy peak.

Irradiation, counting and sample analysis: In this study, instrumental neutron activation analysis (NAA) was performed using an air-driven pneumatic system, known as a "rabbit" system, installed in the horizontal channel B of the Tehran Research Reactor. This setup allowed for both short and long irradiations of the samples, enhancing the analysis process. The samples were irradiated with a neutron beam from channel B of the reactor, which operates at a power of 4.5 MW and provides a thermal neutron flux of approximately 2×10^{12} n/cm^2·s at the irradiation position.

For each tea sample, four randomly selected portions, each weighing approximately 100-300 mg, were prepared for neutron activation analysis (NAA). Both pre- and post-infusion tea leaves were divided into four portions, packed in polyethylene bags and inserted into polyethylene vials. These vials were then transported to the irradiation position near the reactor core using a pneumatic system. Two types of irradiation were performed based on the radionuclide half-lives required for element analysis: short-term irradiation for elements with short-lived radionuclides (such as Al, Ca, K, Mn, Na and Mg) and long-term irradiation for elements with medium- and long-lived radionuclides (such as Br, Fe and Co).

Two irradiation protocols were employed to analyze different elements. For short-term irradiation (for elements such as Mn and Mg), approximately 100-150 mg of each dry tea powder sample (pre- and post-infusion tea leaves) and standard sample were irradiated for 30 sec. After cooling for 15 min, the gamma spectra of these samples were recorded for 300-500 sec. In the long-term irradiation, the dry tea leaves samples and standards, weighing around 200-300 mg, were irradiated for 1 h. The activated samples were cooled for periods ranging from several hours to up to four weeks before their gamma spectra were recorded for 1000-10000 sec using an HPGe detector and

TABLE-1
γ-RAY ENERGY AND HALF-LIFE OF ISOTOPES USED FOR NEUTRON ACTIVATION ANALYSIS IN THIS STUDY

Element	Target, production mode (n,γ)	Isotope abundance (%)	Isotope produced	Half time	Energy (keV)	Branching ratio (%)
Al	Al-27	100	Al-28	2.24 m	1778.99	100
Mg	Mg-26	11	Mg-27	9.46 m	1014.43	28.60
Mn	Mn-55	100	Mn-56	2.58 h	1810.72*, 2113.05	27.19, 14.34
K	K-41	6.73	K-42	12.36 h	1524.58	18.80
Sm	Sm-152	26.7	Sm-153	46.27 h	69.67*, 103.18	4.85, 28.82
Na	Na-23	100	Na-24	14.96 h	1368.60*, 2754	100, 99.94
Br	Br-81	49.4	Br-82	35.3 h	554.35, 776.52*	70.76, 83.54
La	La-139	99.911	La-140	40.27 h	1596.21*	95.40
Ba	Ba-130	0.11	Ba-131	11.8 d	216.05, 496.26*	20.0, 44.00
Co	Co-59	100	Co-60	5.27 y	1173.24*, 1332.50	99.90, 99.98
Cr	Cr-50	4.34	Cr-51	27.7 d	10.08	320.08*
Fe	Fe-58	0.28	Fe-59	44.5 d	1099.25*	59.50
Rb	Rb-85	72.2	Rb-86	18.66 d	1076.60*	8.78
Sc	Sc-45	100	Sc-46	83.81 d	889.28*, 1120.55	99.98, 99.99
Zn	Zn-64	49.2	Zn-65	243.9 d	1115.55*	50.7

Gamma Vision software [20]. The comparative method was applied to determine the concentration of elements by analyzing the spectra with Span software [21]. Table-1 lists the isotopes, half-lives and gamma energies of interest for NAA in this study.

Quality control: The IAEA/V-10 Hay (powder) reference material was used as a standard for calibration. To ensure accuracy, a separate portion of the IAEA-A11 sample and additional V-10 standards were analyzed as unknowns. Multiple analyses were conducted on different portions of each sample, evaluating precision through the comparison of results across different portions. Table-2 provides certified concentrations of elements in the IAEA/V-10 reference material.

TABLE-2
CERTIFIED CONCENTRATIONS OF ELEMENTS DETERMINED IN IAEA/V-10 Hay (POWDER) REFERENCE MATERIAL

Element	Concentration (mg/Kg)	Confident interval at significance level 0.05 (mg/Kg)
Al	47	30-87
Mg	2300	2100-2500
Mn	47	32-52
K	21000	19000-23000
Sm	0.02	0.01-0.03
Na	500	300-900
Br	8	7-11
La	0.07	0.06-0.09
Ba	6	4-7
Co	0.13	0.11-0.14
Cr	6.5	5.6-7.1
Fe	185	177-190
Rb	7.6	7.3-7.8
Sc	0.014	0.012-0.015
Zn	24	21-27

RESULTS AND DISCUSSION

This study analyzed the concentrations of essential and non-essential elements in five brands of black tea available in Iran, including two domestic brands, Noor Jafari and Bahar Lahijan from Gilan province in northern Iran, as well as Shahrzad (imported from India) and Ahmad Ceylon and Golestan Ceylon (both imported from Sri Lanka). Using NAA, the elemental concentrations in dry tea leaves and brewed tea waste were determined, allowing us to estimate their extraction efficiencies and potential dietary contributions for Iranian consumers. The essential elements analyzed were Na, K, Mg, Fe, Zn, Co, Mn and Cr, while non-essential elements included Al, Ba, Rb, Br, La, Sc and Sm. The results are discussed with respect to the concentrations in tea leaves, extraction efficiencies and estimated daily intakes.

Concentration of elements in black tea leaves and comparison with previous studies: The elemental analysis of both dry tea leaves and tea dregs (post-infusion tea waste) highlights notable trends in the retention and solubility of elements during brewing. Tables 3 and 4 detail the concentrations of essential and non-essential elements in five different black tea brands before and after infusion, as determined by NAA.

Descriptive statistics, including mean and standard deviation for each element, were calculated, followed by a one-way ANOVA to assess significant differences in elemental content between dry leaves and tea dregs. The detailed results of the descriptive statistics for these tea samples are presented in Table-5.

In agreement with prior studies on Iranian black tea conducted by various researchers [4,16], the present findings confirm the consistent elemental profiles for essential and toxic elements. Significantly, this work contributes fresh knowledge by identifying trace elements in black tea leaves, including barium (Ba), cobalt (Co), rubidium (Rb), scandium (Sc), lanthanum (La), and samarium (Sm). These elements had not been previously documented in black tea samples from Iran. The elements analyzed in dry tea leaves were categorized based on concentration: major and minor elements (concentrations >100 ppm), including potassium (K), magnesium (Mg), manganese (Mn), iron (Fe), aluminum (Al) and sodium (Na); and trace elements (concentrations <100 ppm), such as bromine (Br), barium (Ba) and cobalt (Co).

TABLE-3
THE CONCENTRATION OF ESSENTIAL AND NON-ESSENTIAL IN DRY BLACK TEA LEAVES SAMPLES (mg/Kg ± %)

Element	Noor Jafari tea	Lahijan tea	Shahrzad tea	Golestan tea	Ahmad Ceylon
Al	143 ± 2.4	214 ± 1.9	86 ± 0.8	–	124 ± 2.2
K	16000 ± 7.2	13000 ± 9.0	21000 ± 7.0	20000 ± 5.4	19000 ± 4.4
Mn	665 ± 0.7	995 ± 0.5	580 ± 0.7	543 ± 0.7	–
Mg	3050 ± 9.0	3480 ± 9.4	2620 ± 6.8	2750 ± 8.7	2690 ± 7.5
Br	4 ± 1.9	4 ± 1.9	3 ± 2.1	2 ± 3.6	4 ± 2.6
Ba)	39 ± 15.7	46 ± 11.1	50 ± 19.7	47 ± 12.0	12 ± 41.1
Co	0.34 ± 4.0	0.35 ± 4.3	0.22 ± 3.3	0.31 ± 3.4	0.14 ± 7.9
Cr	3.4 ± 5.2	2.2 ± 8.5	2.9 ± 3.3	–	–
Fe	282 ± 4.7	235 ± 5.7	–	–	112 ± 10.2
Rb	51.5 ± 3.3	48 ± 3.2	57.6 ± 1.4	53.8 ± 2.2	35.6 ± 3.1
Zn	31 ± 3.2	29 ± 3.7	34 ± 3.8	31 ± 2.6	23 ± 4.8
Na	80 ± 1.7	50 ± 2.8	150 ± 2.2	30 ± 4.5	100 ± 5.1
La	0.47 ± 3.5	0.75 ± 3.0	0.23 ± 7.8	0.24 ± 5.5	0.11 ± 9.5
Sm	0.05 ± 3.1	0.08 ± 8.1	0.03 ± 10	0.03 ± 8.3	0.02 ± 9.4
Sc	0.057 ± 0.33	0.062 ± 3.4	0.021 ± 3.2	0.051 ± 3.9	0.064 ± 4.6

TABLE-4
CONCENTRATIONS OF ESSENTIAL AND NON-ESSENTIAL ELEMENTS IN BREWED BLACK TEA WASTE AFTER INFUSION (mg/Kg)

Element	Noor Jafari tea	Lahijan tea	Shahrzad tea	Golestan tea	Ahmad Ceylon
Al	144 ± 1.6	188 ± 1.6	83 ± 2.9		121 ± 1.9
K	4000 ± 4.3	2000 ± 6.0	5000 ± 6.4	4000 ± 8.7	4000 ± 15.5
Mn	664 ± 0.6	1002 ± 0.5	552 ± 0.7	518 ± 0.7	–
Mg	2830 ± 9.1	3210 ± 9.6	2440 ± 8.9	2160 ± 9.7	1990 ± 8.7
Br	1 ± 3.7	0.8 ± 4.7	2 ± 2.8	1 ± 5.4	1 ± 3.8
Ba	36 ± 10.5	34 ± 10.9	44 ± 12.5	45 ± 9.4	12 ± 32.6
Co	0.23 ± 3.6	0.17 ± 6.8	0.17 ± 7.7	0.24 ± 6.0	0.11 ± 10.8
Cr	1.8 ± 6.8	1.7 ± 9.3	1.6 ± 10.3	–	–
Fe	282 ± 3.2	232 ± 5.6	–	–	115 ± 8.8
Rb	12.3 ± 4.8	7.9 ± 10.2	11.9 ± 8.2	10.9 ± 8.6	8.0 ± 9.2
Zn	28 ± 2.5	25 ± 4.2	31 ± 4.0	27 ± 4.5	21 ± 5
Na	70 ± 1.8	47 ± 2.9	140 ± 4.9	25 ± 3.7	100 ± 2.7
La	0.36 ± 3.9	0.55 ± 3.6	0.24 ± 6.0	0.18 ± 7.5	0.10 ± 8.6
Sm	0.04 ± 4.0	0.06 ± 2.8	0.03 ± 6.8	0.04 ± 5.1	0.02 ± 7.0
Sc	0.055 ± 2.2	0.057 ± 3.4	0.022 ± 6.2	0.045 ± 4.5	0.063 ± 3.6

TABLE-5
DESCRIPTIVE STATISTICS OF ELEMENTAL CONCENTRATIONS AND CORRELATIONS IN BLACK TEA LEAVES BEFORE AND AFTER INFUSION

Element	Mean value of dry tea leaves (mg/Kg) ± SD	Mean value of dry tea dregs (mg/Kg) ± SD	F-statistic	p-value
Al	142 ± 54	134 ± 44	0.049	0.83
K	17800 ± 3271	3800 ± 1095	82.35	1.74e-05
Mn	696 ± 206	684 ± 221	0.006	0.94
Mg	2918 ± 354	2526 ± 497	2.06	0.189
Br	3.4 ± 0.89	1.16 ± 0.47	24.40	0.0011
Ba	38.8 ± 15.51	34.2 ± 13.31	0.253	0.628
Co	0.27 ± 0.09	0.18 ± 0.05	3.56	0.095
Cr	2.83 ± 0.60	1.66 ± 0.11	10.84	0.030
Fe	176 ± 92	176 ± 91	0	1.0
Rb	47.2 ± 8.22	10.2 ± 2.11	95.00	1.02e-05
Zn	30 ± 4	26 ± 4	1.67	0.23
Na	82 ± 46	76 ± 45	0.037	0.85
La	0.36 ± 0.25	0.28 ± 0.17	0.28	0.60
Sm	0.04 ± 0.02	0.038 ± 0.014	0.101	0.75
Sc	0.051 ± 0.017	0.048 ± 0.016	0.05	0.813

The present analysis revealed no notable variations in the elemental concentrations across the five brands. Domestic brands (Noor Jafari and Bahar Lahijan) and imported teas (Shahrzad, Ahmad Ceylon and Golestan Ceylon) displayed similar levels of most elements, with slight increases in aluminum, magnesium, manganese and lanthanum concentrations in domestic brands. Additionally, the iron content was marginally higher in domestic samples. However, given the limited sample size, these differences are not definitive and larger sample sizes are recommended to validate these observations statistically.

An intriguing observation emerged regarding the concentration of certain elements in tea dregs compared to dry leaves before infusion. In some samples, elements like aluminum and iron were present in higher concentrations in tea dregs than in dry leaves before infusion, as illustrated in Table-4. For example, the aluminum content in Noor Jafari tea leaves after infusion was 1 mg/kg higher than before infusion. However, this increase falls within the measurement error, indicating that aluminum solubility during brewing is minimal. Similarly, the iron concentration in Golestan tea leaves increased post-infusion but remained within the error margin, suggesting that iron, too, remains largely insoluble during the brewing process.

When comparing elemental concentrations across brands (Table-5), potassium emerged as the predominant element, followed by magnesium and manganese, consistent with findings by Dambiec *et al.* [6], who reported similarly high potassium levels in black teas. Comparisons with literature [4,16, 22,23] show that the present results align closely with typical concentration ranges for elements like potassium, magnesium and manganese in black teas. Some variations were observed, such as slightly lower sodium levels compared to Dambiec *et al.* [6] and a lower concentration of aluminum than that reported by Malik *et al.* [23], potentially due to the differences in the soil composition, agricultural practices or regional processing methods.

The statistical analysis of the essential and non-essential elements in dry tea leaves before and after infusion, as shown in Table-5, identified significant differences for elements like Rb, K, Br and Cr, with *p*-values of 1.02×10^{-5}, 1.74×10^{-5}, 0.0011 and 0.03, respectively. These findings indicate a high extraction efficiency for these elements into the tea infusion. Conversely, elements such as Co, Mg and Zn exhibited decreased concentrations in tea dregs after infusion compared to dry black tea leaves, though these changes were not statistically significant (p = 0.095, 0.189 and 0.23, respectively). Although the differences lack statistical significance, the relatively low *p*-values suggest a potential trend worth further investigation. Expanding the sample size or implementing more controlled experimental conditions could help determine whether a stronger relationship exists for these elements between dry tea leaves and post-infusion tea waste.

Extraction efficiency of elements in tea infusions: To determine the extraction levels of 15 essential and non-essential elements during the brewing process, we compared their concentrations in black tea leaves before infusion (Table-3) and after infusion (Table-4). Table-6 summarizes the extraction levels for each of the five black tea brands, showing how much of each element is transferred into the tea infusion. Moreover, the mean concentration of each element's extraction across the five brands is presented in Table-7, providing an overall view of element solubility in tea infusions.

TABLE-6
EXTRACTION OF ESSENTIAL AND NON-ESSENTIAL ELEMENTS FROM DRY BLACK TEA LEAVES SAMPLES INTO TEA INFUSION DURING BREWING (mg/Kg)

Element	Noor Jafari Tea	Lahijan tea	Shahrzad Tea	Golestan Tea	Ahmad Ceylon
Al	-1	26	3	–	3
K	12000	11000	15000	16000	15000
Mn	1	-7	28	25	
Mg	220	270	180	590	700
Br	3	3.2	1	1	3
Ba	33	12	6	2	0
Co	0.11	0.18	0.05	0.07	0.03
Cr	1.6	0.5	1.3	–	–
Fe	0	3	–	–	-3
Rb	39.2	40.1	45.7	42.9	34.2
Zn	3	4	3	4	2
Na	10	3	10	5	0
La	0.11	0.2	0	0.06	0.01
Sm	0.01	0.02	0	0.01	0
Sc	0.002	0.05	0	0.006	0.001

The extraction efficiency of each element into the tea infusion for the five tea brands was determined by calculating the ratio of its concentration in the infusion (Table-6) to its concentration in the dry tea leaves (Table-3). Using these concentration values from dry tea leaves and the corresponding infusions, we calculated the extraction efficiencies for both essential and non-essential elements, with results displayed in Tables 8 and 9.

Furthermore, the mean extraction efficiency across all samples is summarized in Table-7. The extraction efficiency, or transfer rate of each element from tea leaves to infusion were evaluated. As shown in Table-7, the elements with high extraction efficiencies (>55%) include rubidium, potassium, bromine and chromium, with average transfer rates of 79.31%, 78.65%, 65.88% and 61.32%, respectively. These high solubility rates suggest that a significant portion of these elements dissolves into the tea infusion, which may affect its nutritional content

TABLE-7
MEAN ELEMENT CONCENTRATIONS IN DRY TEA LEAVES AND TEA INFUSION, EXTRACTION EFFICIENCY AND ESTIMATED DAILY INTAKE (EDI) FOR IRANIAN CONSUMERS ACROSS FIVE TEA BRANDS

Elements	Mean element extracted into tea infusion (mg/Kg)	Extraction efficiency (%)	Mean estimated daily intake of tea infusion (EDI) (mg/Day)	Daily nutritional requirements		Percentage contribution to the dietary needs (%)
Al	7.75	5.46	0.034	3.5 (1.8-8.4) mg	[Ref. 24]	0.97
K	14000	78.65	61	M: 3400 mg; F: 2600 mg	[Ref. 25]	M: 1.8; F: 2.35
Mn	11.75	1.68	0.05	M: 2.3 mg; F: 1.8 mg	[Ref. 25]	M: 2.17; F: 2.7
Mg	392	13.433	1.71	M: 420 mg; F: 320 mg	[Ref. 25]	M: 0.41; F: 0.53
Br	2.24	65.88	0.01	2.97 (0.627-16.9) mg	[Ref. 26]	0.33
Ba	4.6	11.85	0.02	0.685 mg	[Ref. 27]	2.92
Co	0.088	32.35	0.0004	5-8 mcg	[Ref. 28]	5-8
Cr	1.13	39.92	0.0049	M: 35 mcg; F: 25 mcg	[Ref. 29]	M: 14; F: 19.6
Fe	0	0	0	M: 8 mg; F: 18 mg	[Ref. 25]	0
Rb	39.1	79.31	0.17	2.2 mg	[Ref. 30]	7.7
Zn	3.2	10.81	0.014	8-14 mg	[Ref. 31]	0.1-0.25
Na	5.6	6.82	0.02	1525 mg	[Ref. 32]	0.001
La	0.074	20.55	0.0003	150 mcg	[Ref. 33]	0.1
Sm	0.004	9.52	0.00002			
Sc	0.0026	5.09	0.00001	0.1 mcg	[Ref. 34]	10

TABLE-8
EXTRACTION EFFICIENCY (%) OF ESSENTIAL ELEMENT (mg/Kg) IN TEA INFUSIONS

Sample	Na	K	Mg	Fe	Zn	Co	Mn	Cr
Noor Jafari tea	12.5	75	7	0	9.6	32.3	0.1	47.1
Lahijan tea	6	84.6	7.8	1	13.7	51.4	0	22.7
Shahrzad tea	6.6	71.4	6.8	–	8.8	22.7	4.8	44.82
Golestan tea	16.6	80.0	21.4	–	12.9	22.5	4.6	–
Ahmad Ceylon	0	78.9	26.0	0	8.6	21.4	–	–

TABLE-9
EXTRACTION EFFICIENCY (%) OF NON-ESSENTIAL ELEMENT (mg/Kg) IN TEA INFUSIONS

Sample	Al	Ba	Rb	Br	La	Sc	Sm
Noor Jafari tea (A)	0	7.6	76.1	75	23.4	3.5	20
Lahijan tea	12.1	26.08	83.5	80	26.6	8.0	25
Shahrzad tea	3.4	12	79.3	33.3	0	0	0
Golestan tea	–	4.2	79.7	50	25	0	11.7
Ahmad Ceylon	2.4	0	77.5	75.0	9.09	1.5	0

and safety profile. This finding is consistent with the ANOVA results presented earlier in this study (Table-5), where these elements exhibited statistically significant differences ($p < 0.05$) between their concentrations in tea leaves and corresponding infusions.

Moderately extractable elements (20-55%) included cobalt and lanthanum, with transfer rates of 32.35% and 20.55%, respectively. Elements with low extraction efficiencies (< 20%) included magnesium (13.4%), barium (11.83%), zinc (10.81%), samarium (9.52%), sodium (6.82%), aluminum (5.46%) and scandium (5.09%). Notably, iron and manganese showed minimal transfer (<1%), consistent with findings by Dambiec *et al.* [6], indicating their low bioavailability in tea infusions. This limited transfer of iron, despite its essential role, is likely due to the presence of phytochemicals in tea that inhibit its release.

The findings on the extraction efficiency for potassium and bromine (80-90%) are consistent with the results of Mahani & Maragheh [16], although the present values are slightly lower. Dambiec *et al.* [6] reported similar transfer rates for potassium, highlighting the comparably high solubility of this element across studies. However, the extraction efficiency for other elements, such as magnesium and manganese, varied. For instance, Salahinejad & Aflaki [4] reported an extraction efficiency of 25.82% for magnesium in Iranian tea, slightly lower than the present findings, which may be due to methodological differences in infusion preparation.

Contribution of black tea to estimate daily mineral intake among Iranians: The substantial daily intake of black tea by Iranians, averaging 5 to 6 cups, prompts an important debate on the extent to which their daily mineral needs can be fulfilled through tea consumption. This section examines the nutritional importance of selected essential and non-essential elements and evaluates what proportion of daily mineral requirements can potentially be supplied through tea, based on average daily consumption and comparisons with established recommended daily intakes. In Iran, the average annual per capita consumption of black tea leaves is 1.6 kg, equating to a daily intake of approximately 4.38 g per person [3]. To estimate the daily intake of essential and non-essential elements from black tea infusions for Iranian consumers, we analyzed five different tea brands. By combining the element concentrations found in the dry tea leaves with the extraction efficiency of each element, we calculated the daily intake values for each element for each tea brands. The detailed results of these calculations are presented in Table-10.

Using the daily nutritional requirements reported in the literature and the estimated daily intake of elements from tea infusion calculated in this study, the percentage contribution of tea consumption to the dietary needs of key elements for Iranians was also determined. These findings are summarized in Table-10, which presents the average daily intake of various elements from the five black tea samples analyzed. By comparing these intake levels with the recommended daily requirements, we evaluate tea's role in meeting essential trace element needs for Iranians.

The results in Table-7 show that tea consumption makes a significant contribution to the dietary needs for chromium, one of the essential trace elements analyzed in tea infusion. With recommended daily intakes of approximately 35 µg for men and 25 µg for women, the findings indicate that daily tea consumption can fulfill about 14% of the daily chromium requirement for Iranian men and around 19.6% for Iranian women. Following chromium, scandium also contributes meaningfully, with tea

TABLE-10
ESTIMATED DAILY INTAKES (EDI) (mg/day) OF NON-ESSENTIAL ELEMENTS FOR CONSUMERS DUE TO TEA INFUSION IN IRAN

Sample	Al	Ba	Rb	Br	La	Sc	Sm
Noor Jafari tea (A)	0	0.013	0.171	0.013	0.00048	0.000008	0.00004
Lahijan tea	0.11	0.052	0.175	0.01	0.0008	0.000002	0.000009
Shahrzad tea	0.013	0.026	0.200	0.004	0	0	0
Golestan tea	–	0.009	0.188	0.004	0.0003	0	0.000026
Ahmad Ceylon	0.013	0	0.120	0.013	0.000004	0.0000004	0

providing about 10% of the daily requirement and rubidium intake from tea makes up around 7.7% of the recommended daily intake.

For cobalt, another essential element, tea provides an estimated 5–8% of daily requirements, though intake can vary with individual consumption habits and other dietary factors. Barium contributes about 2.9% of the daily requirement, while potassium and manganese, despite high extraction efficiency and solubility in tea infusions, each meet only around 2% of the daily requirement.

A specific concern for some, particularly pregnant women, is the intake of aluminum due to its relatively high content in tea leaves. However, given aluminum's low solubility in water, its concentration in tea infusions is minimal, thereby reducing any potential risk from tea consumption. The remaining elements analyzed in this study contribute less than 1% to daily requirements. These results provide insight into the role of black tea in supplementing daily micronutrient intake among Iranians, highlighting it as a secondary source of certain trace elements. Further research is recommended to explore the broader dietary impact of tea consumption on essential element intake across various populations and dietary contexts.

Implications for health and safety: The Codex Alimentarius Commission [35] has set permissible daily intake limits for certain elements considered contaminants, even though they are not classified as toxic metals. These elements, including aluminum and zinc, require regulation due to potential health impacts, though they are generally less harmful than toxic metals. The recommended acceptable daily intake for a 60 kg adult is set at 120 mg for aluminum and 60 mg for zinc.

The high solubility of essential elements like potassium is beneficial, as it supports nutritional needs. However, the extraction of non-essential or potentially toxic elements, such as aluminum and zinc, raises health concerns due to their potential to accumulate in the body and cause adverse effects over time. In the tested tea samples, aluminum concentrations were lower than levels reported in some studies [23]. Nevertheless, even at a low extraction rate, the presence of aluminum warrants attention due to its potential neurotoxicity with prolonged exposure.

Conclusion

This study provides a comprehensive analysis of essential and non-essential elemental concentrations in 5 popular black tea brands in Iran, utilizing neutron activation analysis (NAA) to assess both dry tea leaves and post-infusion tea waste. The findings offer valuable insights into the elemental composition and extraction efficiency of various elements, contributing to a better understanding of tea's nutritional role and potential health implications for Iranian consumers. The analysis reveals that, on average, elements such as potassium, rubidium, bromine and chromium demonstrate high extraction efficiency into the tea infusion, underscoring their bioavailability in tea consumption. Essential elements like chromium and scandium, though present in small amounts, provide a modest contribution toward daily dietary requirements. For instance, daily tea consumption can meet up to 14-20% of the chromium requirement for adults, highlighting tea's supplementary role in micronutrient intake. While the most essential elements contribute minimally to daily requirements, the low extraction rates of potentially harmful elements, such as aluminum and iron, suggest a limited health risk from tea consumption under normal dietary practices. However, given the popularity of black tea in Iran and its frequent consumption, monitoring for certain trace elements remains important, especially for vulnerable populations, such as pregnant women. Overall, the results in this study support black tea's position as a modest yet beneficial contributor to trace element intake in the Iranian diet. However, further research on different tea varieties, larger sample sizes and longitudinal studies could provide a more comprehensive view of tea's role in dietary intake and potential health implications in diverse populations.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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