



Is Spirulina safe in terms of heavy metals? A public health risk assessment

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Received: 25 January 2026 / Revised: 2 April 2026 / Accepted: 4 May 2026
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Abstract

Spirulina is a microalga/cyanobacterium widely consumed as a dietary supplement due to its high nutrient content and health benefits. While Spirulina is recognized for its contribution to daily mineral intake (e.g., iron, manganese, magnesium, and potassium), its ability to bind heavy metals raises safety concerns, particularly for vulnerable age groups. This study analyzed eight commercial Spirulina supplements (powder and tablet forms) consumed in Türkiye for heavy metal and macro-mineral content using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The health risks were assessed across various age groups, including pregnant and breastfeeding women. Significant variability was found in heavy metal and mineral concentrations among the supplements, with one sample (S3) exceeding acceptable Hazard Index (HI) levels for all age groups except adults. Notably, Spirulina supplements generally did not exceed the established dietary reference values or Codex limits for heavy metals, except in certain younger age groups where potential non-carcinogenic risks were observed. The results emphasize the importance of determining safe consumption levels for Spirulina and other algae-based supplements to mitigate risks while maximizing their nutritional benefits. Additionally, the findings highlight the need for public health guidelines to standardize Spirulina's daily intake and labeling practices.

Keywords *Arthrospira platensis* · *Limnospira platensis* · Heavy metals · Mineral composition · Public health · Spirulina

Introduction

The growing global population faces major challenges, including water pollution, climate change, energy shortages, and food safety and security. Growing awareness of healthy lifestyles and environmental sustainability has driven interest in nutrient-rich, sustainable food sources, such as microalgae-based products (Diaz et al. 2023).

Microalgae, including both eukaryotic microalgae and prokaryotic photosynthetic cyanobacteria, have been utilized as a food source for millennia. Among these, *Arthrospira*, a genus of filamentous cyanobacteria often referred to as "blue-green algae," is notable for its nutritional benefits. Among these, *Arthrospira platensis* and *Arthrospira maxima*, (these species have recently been reclassified as *Limnospira platensis* and *L. maxima*; Nowicka-Krawczyk et al. 2019; Santos et al. 2023) commonly known as Spirulina, are extensively studied and widely consumed in both human and animal nutrition due to their high protein content and rich nutrient profile (Neher et al. 2018). *Arthrospira platensis* is the most widely available and extensively studied species, and most research publications and public health

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recommendations concerning *Spirulina* primarily refer to this species (Ahmad et al. 2023; Sonawane et al. 2023).

Spirulina is considered a functional food due to its rich composition of complete proteins, essential fatty acids, vitamins, minerals, and bioactive compounds such as carotenoids, chlorophyll, xanthophylls, and phycocyanin. These properties make it a valuable ingredient for product formulations across the food industry, including applications as a natural colorant, thickener, stabilizer, gelling agent, and emulsifier (Üstün-Aytekin et al. 2022; Franco-Morgado et al. 2023). Additionally, *Spirulina* exhibits notable health benefits, including antioxidant, antihyperglycemic, antihyperlipidemic, antihypertensive, and anti-obesity effects, as well as the ability to mitigate heavy metal toxicity (Abdel-Daim et al. 2018; Yousefi et al. 2018; Ghaem Far et al. 2021; Gültaş et al. 2021; Mallamaci et al. 2023).

Spirulina, a cyanobacterium that naturally thrives in alkaline lakes, is commercially cultivated in large-scale outdoor ponds or controlled greenhouse systems. This cultivation approach enables optimization of growth parameters to meet industrial demands. Beyond its role as a food source, *Spirulina* is widely used in the phytoremediation of heavy metals from contaminated water sources, demonstrating its environmental benefits (Palaniswamy and Veluchamy 2017; Padgaonkar et al. 2022). The biosorption capabilities of microalgae, including *Spirulina*, are attributed to the presence of functional groups such as amino, carboxyl, sulfate, and hydroxyl groups on their cell surfaces. These groups facilitate the binding of metal ions, making microalgae particularly effective in removing heavy metals from their surroundings. Furthermore, microalgae have evolved to express specific peptides, such as phytochelatins, that enhance their capacity to sequester heavy metals (Leong and Chang 2020).

Typically, microalgae are cultivated in surface or groundwater supplemented with commercial fertilizers to provide essential nutrients. However, this practice can lead to the accumulation of heavy metals and other toxic substances from these water sources used (Al Dhabbi 2013; Muys et al. 2019). To further reduce production costs and resource use, some manufacturers incorporate wastewater into the cultivation process, raising additional concerns about potential contamination (Özlu and Bayram 2022). This dual role of *Spirulina* in nutrition and environmental remediation highlights its importance while also underscoring the need for stringent quality control measures during cultivation.

Heavy metals represent a significant environmental challenge with profound implications for public health due to their toxicity, persistence, and bioaccumulation in the human body (Abd Elnabi et al. 2023; Musah 2025). Lead, cadmium, and arsenic can accumulate in food chains and pose substantial health risks by disrupting essential metabolic processes even at low exposure levels (Mititelu

et al. 2025). The World Health Organization (WHO) (2011) lists the following as the main heavy metals: beryllium, aluminum, chrome, manganese, iron, cobalt, nickel, copper, zinc, arsenic, selenium, molybdenum, silver, cadmium, tin, antimony, barium, mercury, thallium, and lead. Some of these heavy metals are necessary for humans in minute amounts (cobalt, chrome, copper, nickel) while others are carcinogenic or toxic, affecting, among others, the central nervous system (mercury, lead, arsenic), the kidneys or liver (mercury, lead, cadmium, copper) or skin, bones, or teeth (nickel, cadmium, copper, chrome). WHO has identified cadmium, lead, and arsenic among the top 10 chemicals posing considerable risks to public health.

Despite its nutritional benefits, *Spirulina*'s capacity to bind and accumulate metals raises important safety concerns when consumed as a dietary supplement (Wu et al. 2016). Recently, similar concerns have been raised for other specialized food categories, such as food for special medical purposes (FSMPs), where the balance between essential nutrients and heavy metal exposure (mercury, lead, cadmium, and arsenic) is critical for vulnerable patient groups (Frydrych et al. 2024). To mitigate these risks, it is essential to conduct thorough heavy metal analyses on *Spirulina* products intended for human consumption.

The Food and Drug Administration (FDA) (2023) has set limits for lead, arsenic, and mercury for *Spirulina* extract in the listing of color additives exempt from certification. Despite this, no prior research has specifically evaluated the heavy metal content in *Spirulina* supplements consumed in Turkey, nor has any study assessed the associated health risks for different age groups, including pregnant and breastfeeding women, in this context.

This study seeks to address these gaps by quantifying levels of heavy metals and macro minerals in *Spirulina* supplements commonly consumed in Türkiye using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Additionally, it aims to evaluate the potential health risks posed by heavy metals across various age groups, including pregnant and breastfeeding women, and to offer critical insights into the safety of *Spirulina* consumption in these populations.

Materials and methods

Samples

A total of eight different commercial brand products of *Spirulina*, including two in powder form and six in tablet form, commonly consumed in Turkey, were purchased from pharmacies and local markets in Istanbul. The products were selected based on their commercial availability and accessibility. All products were within their expiration dates.

Table 1 Information about the analyzed Spirulina supplements in this study

Supplements Number	Form	Species	Origin	Average Daily Dose Recommendations ^a (g)	Maximum Daily Dose Recommendations (g)	Age Recommendation Specified on the Label
S1	Powder	<i>A. platensis</i>	China	7.5	10	None
S2	Powder	<i>A. platensis</i>	China	5	5 ^b	None
S3	Tablet	<i>A. platensis</i>	Turkey	2.25	3	None
S4	Capsule	<i>A. platensis</i>	Turkey	2.01	2.01 ^b	Adults
S5	Tablet	<i>A. platensis</i>	China	6	6 ^b	None
S6	Capsule	<i>A. platensis</i>	Turkey	4.32	4.32 ^b	>11 years
S7 ^c	Capsule	<i>A. platensis</i>	Turkey	1.5	1.5 ^b	Adults
S8	Tablet	<i>A. platensis</i>	Turkey	0.75 2	1 2,5	4–10 years: 1–2 tablet >11 years: 3–5 tablet

^aAverage Daily Dose Recommendations: These values were calculated by taking the average of the minimum and maximum values specified on the product labels. ^bThese values were the recommended doses on the product labels. Therefore, we accepted them as the maximum dose. ^cThe product contains kelp, nettle, and tricalcium phosphate

Details on the Spirulina supplements, including their form, species, and origin, are provided in Table 1. Images of the analyzed samples are provided in the supplementary material (Fig. S1).

Analysis by the ICP-MS method

In this study, ICP-MS was used for its high sensitivity, wide dynamic range, and capability to perform simultaneous multi-element analysis (Wilschefska and Baxter 2019; Huang and Li 2025). For the analysis, all Spirulina supplements, except for the powder form, were ground. A sample of 0.3 g of the ground material was weighed and dissolved in a mixture of 6 mL of concentrated nitric acid and 4 mL of hydrochloric acid (Merck, Germany) using a microwave digestion system (Cem Corporation MARS 5 Digestion) (U.S. Environmental Protection Agency 1996). The resulting solution was then filtered. A 1 mL aliquot of each filtrate was diluted to 15 mL with ultrapure water. All samples were subsequently placed in the autosampler unit of the ICP-MS instrument (Thermo Scientific iCAP RQ) for analysis (U.S. Environmental Protection Agency 2014). Calibration solutions were prepared by serial dilutions using ICP-multi element standard solution-IV (1000 mg L⁻¹) (Supelco 1.11355.0100, Merck, Germany). Each analysis was performed in triplicate. All reagents used were of analytical grade.

Health risks assessment

To assess health risks associated with Spirulina consumption, the estimated daily intake (EDI) was calculated using the formula:

$$EDI = (M \times C) / BW$$

where M is the maximum recommended daily amount (kg day⁻¹, converted from g day⁻¹ for calculation purposes) on the labels of Spirulina supplements, C is the elemental concentration (mg kg⁻¹) of Spirulina supplements, and BW is the body weight. Health risks were calculated for five age groups: ≥ 21 , 16 to < 21, 11 to < 16, 6 to < 11, 2 to < 6 years, and pregnant and breastfeeding women. The reference body weights, as estimated by the Agency for Toxic Substances and Disease Registry (ATSDR) (2023), were used to evaluate the health risks of these groups. These values are 80, 71.6, 56.8, 31.8, 17.4, and 73 kg, respectively.

Chronic daily intake (CDI) was calculated using the formula:

$$CDI = (EDI \times ED_{tot}) / BW$$

where ED_{tot} is the exposure duration (years). The ED_{tot} was assumed to be 70 years for all groups, consistent with a lifetime exposure scenario commonly used in health risk assessment (ATSDR, 2016).

The Target Hazard Quotient (THQ), which indicates the non-carcinogenic potential health risk caused by exposure to the chronic intake of relevant elements, was calculated using the formula:

$$THQ = CDI / RfD_o$$

where RfD_o is defined as consumers' daily oral exposure estimate over a long time without experiencing harmful effects and is a specific value for the trace element being assessed. The RfD_o values used for Al, Pb, Cd, Cr, B, Co, Cu, Fe, Mn, Ni, Ag, and Zn are 1, 0.0035, 0.0005, 1.5, 0.02, 0.0003, 0.0004, 0.64, 0.14, 0.02, 0.005 and 0.3 mg kg⁻¹ day⁻¹, respectively (Antoine et al. 2017; U.S. Environmental Protection Agency 2024; Chebli et al. 2025)

If THQ is <1, non-carcinogenic health effects are not expected. However, if THQ >1, there is a potential for

adverse health effects. To evaluate cumulative potential risk, the Hazard Index (HI) was calculated by summing the THQ values for each heavy metal. If $HI < 1$, the risk is acceptable and considered safe for human consumption; however, if $HI > 1$, consumption may pose a potential health concern (Chebli et al. 2025).

Statistics

Statistical analysis was conducted using SPSS software (Version 29.0 for Windows, USA). The normality of continuous variables was assessed using the Shapiro-Wilk test.

For variables with a normal distribution, means and standard deviations are reported. For variables that did not follow a normal distribution, median values are presented.

Results

In this study, the eight *Spirulina* supplements in Türkiye were analyzed for their heavy metal and macro-mineral content. The data obtained were systematically evaluated, as summarized in Table 2., which displays the concentrations of heavy metals (aluminum, boron, cadmium,

Table 2 The heavy metals and macro minerals content of *Spirulina* supplements (mg kg^{-1}) in this study

Supplements	Calcium	Magnesium	Potassium	Aluminum	Boron	Cadmium	Chromium	Cobalt	Copper
S1	1,925.98 ± 7.70	3,826.13 ± 0.03	11,983.71 ± 35.95	193.25 ± 4.06	11.30 ± 0.15	0.12 ± 0.00	3.16 ± 0.05	0.47 ± 0.00	0.50 ± 0.01
S2	516.28 ± 4.13	3,032.73 ± 6.07	9,741.86 ± 0.00	25.63 ± 0.23	38.15 ± 0.34	0.03 ± 0.00	1.04 ± 0.02	0.24 ± 0.00	1.50 ± 0.02
S3	775.01 ± 12.40	3,019.81 ± 9.06	11,208.70 ± 0.00	45.64 ± 0.18	13.27 ± 0.31	0.32 ± 0.00	24.18 ± 0.22	1.78 ± 0.00	3.11 ± 0.04
S4	2,501.61 ± 35.02	6,266.08 ± 50.13	14,336.84 ± 0.00	72.61 ± 0.58	4.72 ± 0.06	0.12 ± 0.00	5.74 ± 0.17	1.13 ± 0.01	9.53 ± 0.23
S5	2,012.98 ± 6.04	3,454.38 ± 65.63	12,189.89 ± 243.8	189.49 ± 6.44	18.03 ± 0.32	0.11 ± 0.01	14.13 ± 0.28	0.36 ± 0.01	2.18 ± 0.04
S6	1,212.17 ± 6.06	4,049.45 ± 56.69	12,348.61 ± 24.7	201.51 ± 1.01	11.35 ± 0.06	0.09 ± 0.01	1.71 ± 0.02	0.25 ± 0.00	0.96 ± 0.02
S7	6,219.48 ± 62.19	1,757.03 ± 35.14	8,211.03 ± 82.11	60.86 ± 0.97	12.82 ± 0.28	0.18 ± 0.00	3.08 ± 0.02	0.39 ± 0.01	0.98 ± 0.02
S8	38,759.30 ± 620.15	2,709.21 ± 21.67	9,239.51 ± 0.00	137.22 ± 1.51	12.84 ± 0.02	0.19 ± 0.00	2.94 ± 0.01	0.46 ± 0.00	1.84 ± 0.02
Mean	6,740.35	3,514.35	11,157.52	115.78	15.31	0.15	7.00 (3.12)	0.64 (0.43)	2.57 (1.67)
(Median)	(1,969.48)	1,318.66	1,987.19	72.87	(12.83)	0.09	8.09	0.54	2.93
SD	13,059.55				9.92				
Supplements	Indium	Iron	Lead	Manganese	Nickel	Silver	Titanium	Zinc	
S1	0.01 ± 0.00	587.13 ± 6.46	0.51 ± 0.01	26.90 ± 0.05	3.16 ± 0.05	1.05 ± 0.04	0.05 ± 0.00	6.44 ± 0.08	
S2	0.07 ± 0.00	254.96 ± 1.53	0.13 ± 0.00	15.91 ± 0.11	1.45 ± 0.02	1.83 ± 0.03	0.04 ± 0.00	4.08 ± 0.13	
S3	0.01 ± 0.00	522.48 ± 6.79	0.03 ± 0.00	33.14 ± 0.43	65.75 ± 1.18	0.69 ± 0.02	0.19 ± 0.01	8.26 ± 0.05	
S4	0.08 ± 0.00	581.82 ± 4.65	0.72 ± 0.02	94.70 ± 2.37	4.48 ± 0.07	0.06 ± 0.00	0.02 ± 0.00	47.23 ± 0.76	
S5	0.01 ± 0.00	672.21 ± 12.10	0.34 ± 0.01	24.91 ± 0.20	10.47 ± 0.12	0.02 ± 0.00	0.05 ± 0.00	51.38 ± 0.67	
S6	0.02 ± 0.00	411.47 ± 1.65	0.52 ± 0.01	23.81 ± 0.17	2.61 ± 0.05	0.02 ± 0.00	0.08 ± 0.00	17.25 ± 0.33	
S7	0.03 ± 0.00	181.90 ± 1.46	0.23 ± 0.01	14.86 ± 0.18	8.88 ± 0.12	0.31 ± 0.00	0.08 ± 0.00	10.14 ± 0.07	
S8	0.01 ± 0.00	328.25 ± 7.88	0.32 ± 0.01	22.06 ± 0.26	7.62 ± 0.03	1.66 ± 0.01	0.07 ± 0.00	21.24 ± 0.28	
Mean	0.03 (0.02)	442.53	0.35	32.04	13.05 (6.05)	0.70 (0.50)	0.07 (0.06)	20.75	
(Median)	0.03	175.90	0.23	(24.36)	21.53	0.74	0.05	(13.70)	
SD				25.99				18.53	

SD: Standard deviation. Median values are given in parentheses for non-parametric variables

chromium, cobalt, copper, indium, iron, lead, manganese, nickel, silver, titanium, zinc) and macro minerals (calcium, magnesium, potassium) across the examined Spirulina supplements.

The results indicate that potassium (11,157.52 mg kg⁻¹), calcium (6,740.35 mg kg⁻¹), magnesium (3,514.35 mg kg⁻¹), and iron (442.53 mg kg⁻¹) were the most abundant minerals, whereas indium (0.03 mg kg⁻¹) was the least prevalent heavy metal.

Among the supplements, S8 exhibited the highest calcium concentration (38,759.30 mg kg⁻¹), whereas S4 had the highest magnesium (6,266.08 mg kg⁻¹) and potassium (14,336.84 mg kg⁻¹) concentrations. The highest concentrations of cadmium (0.32 mg kg⁻¹), chromium (24.18 mg kg⁻¹), cobalt (1.78 mg kg⁻¹), titanium (0.19 mg kg⁻¹), and nickel (65.75 mg kg⁻¹) were detected in S3.

Aluminum was most prevalent in S6 (201.51 mg kg⁻¹), while boron (38.15 mg kg⁻¹) and silver (1.83 mg kg⁻¹) were highest in S2. S5 contained the highest levels of zinc (51.38 mg kg⁻¹) and iron (672.21 mg kg⁻¹). Finally, S4 exhibited the highest concentrations of manganese (94.70 mg kg⁻¹), lead (0.72 mg kg⁻¹), indium (0.01 mg kg⁻¹), and copper (9.53 mg kg⁻¹).

The maximum and average recommended daily doses for the Spirulina supplements analyzed ranged from 1.5 to 10 g and 1.5 to 7.5 g, respectively. In this study, heavy metal and macro-mineral levels were calculated based on the average recommended and maximum daily doses (mg day⁻¹) listed on the product labels as shown in Table 3.

For adults (>21 years), the EDI and CDI values for heavy metals across all Spirulina supplements were below the RfD thresholds, with the THQ and HI values remaining under 1. However, varying results were observed across other age groups (Tables 4 and 5). For supplement S7, the HI levels did not exceed 1 in any age group, indicating no significant non-carcinogenic risk. In contrast, for supplement S3, HI levels exceeded 1 in all age groups except adults, suggesting a potential health risk for younger individuals.

In the 16 to <21 and 11 to <16 age groups, the HI for supplement S3 exceeded 1, with values of 1.0905 and 1.7329, respectively, indicating a potential health risk. For all other supplements, the HI remained below 1. Additionally, in all supplements, the EDI and CDI values were below RfD, and the THQ was below 1.

In the 6 to <11 age group, while EDI values for all supplements were below the RfDs, the CDI for supplement S3 exceeded the RfD for cobalt (0.0007) and nickel (0.0273). The THQ values for cobalt in S1 and S3 were calculated as 1.0845 and 2.4643, respectively, exceeding the threshold of 1. Additionally, the THQ for nickel in S3 was 1.3654, also exceeding 1. For this age group, the HI values were above 1 for supplements S1 (2.9241), S2 (1.5625), S3 (5.5286), S4 (2.2429), and S5 (1.6945).

In the 2 to <6 age group, the EDI for cobalt and nickel in supplement S3 exceeded the RfDs (0.0006 and 0.0227, respectively). The CDI also exceeded the RfDs for boron and cobalt in S1, boron in S2, cobalt, copper, iron, and nickel in S3, cobalt and copper in S4, and cobalt and iron in S5 (values: 0.0261, 0.0011, 0.0441, 0.0025, 0.0043, 0.7248, 0.0912, 0.0008, 0.0066, 0.004, 0.6714). The THQ values for boron, cobalt, and iron in S1, boron in S2, cobalt, iron, manganese, and nickel in S3, cobalt, iron, and manganese in S4, and cobalt, iron, and manganese in S5 also exceeded 1 (values: 1.3063, 3.6222, 2.1211, 2.2051, 8.2309, 1.1325, 2.2987, 4.5605, 2.6126, 3.2843, 1.1986, 1.0491, 1.2440). Consequently, for this age group, the HI exceeded 1 for all supplements except S7 (S1: 9.7667, S2: 5.2188, S3: 18.4660, S4: 7.7915, S5: 5.6599, S6: 1.8503, S8: 1.2096).

For pregnant and breastfeeding women, the EDI and CDI values for all supplements were below the RfDs, and the THQ values were also below 1. However, the HI for supplement S3 slightly exceeded 1 (1.0491), while all other supplements had HI values below 1.

Discussion

In studies evaluating Spirulina supplements the values obtained for heavy metals and macro minerals show notable differences (Table 6). The differences in macro mineral content among Spirulina cultivated in the USA, Europe, the Middle East, and Asia are quite striking. Rzymiski et al. (2019) found that the levels of aluminum (2,155.6 ± 1,774.7 mg kg⁻¹), cadmium (0.125 ± 0.055 mg kg⁻¹), lead (2.6 ± 1.9 mg kg⁻¹), and iron (368.5–2,528.6 mg kg⁻¹) were higher than those found in our study. Similarly, Janda-Milczarek et al. (2023) reported iron concentrations between 212.23 and 2,785.82 mg kg⁻¹ and zinc levels between 7.068 and 322.14 mg kg⁻¹, exceeding the values reported in our findings. These differences may be attributed to various factors, including the quality and source of water used for Spirulina cultivation, variations in growth conditions, the type and quality of fertilizers applied, geographical and climatic differences, transportation and storage conditions, and differences in processing techniques. Such variability underscores the need for standardized cultivation and processing protocols to ensure consistent quality and safety of Spirulina supplements across different regions.

The maximum and average recommended doses indicated on the labels of the Spirulina supplements in our study ranged from 1.5 to 10 g and 1.5 to 7.5 g, respectively. Notably, the disparity between these minimum and maximum values is substantial. The concentrations of heavy metals and macro minerals across the samples demonstrated significant variability. For example, the aluminum concentration in sample S6 was 201.51 mg kg⁻¹, while it was only 25.63

Table 3 Heavy metal and macro mineral levels calculated based on the average recommended and maximum daily doses (mg day⁻¹) for stated on the labels of Spirulina supplements

Supplements	Calcium		Magnesium		Potassium		Aluminum		Boron	
	A	B	A	B	A	B	A	B	A	B
S1	14.4449	19.2598	28.6959	38.2613	89.8778	119.8371	1.4494	1.9325	0.0848	0.1130
S2	2.5814	2.5814	15.1637	15.1637	48.7093	48.7093	0.1281	0.1281	0.1907	0.1907
S3	1.7438	2.3250	6.7946	9.0594	25.2196	33.6261	0.1027	0.1369	0.0299	0.0398
S4	5.0282	5.0282	12.5948	12.5948	28.8170	28.8170	0.1460	0.1460	0.0095	0.0095
S5	12.0779	12.0779	20.7263	20.7263	73.1393	73.1393	1.1370	1.1370	0.1082	0.1082
S6	5.2366	5.2366	17.4936	17.4936	53.3460	53.3460	0.8705	0.8705	0.0490	0.0490
S7	9.1551	9.1551	2.5863	2.5863	12.0866	12.0866	0.0896	0.0896	0.0189	0.0189
S8 (>11 years)	77.5186	96.8982	5.4184	6.7730	18.4790	23.0988	0.2744	0.3430	0.0257	0.0321
S8 (4–10 years)	29.0695	38.7593	2.0319	2.7092	6.9296	9.2395	0.1029	0.1372	0.0096	0.0128
Mean (Median)	15.6389 (7.1624)	18.8977 (8.1005)	13.3930	15.3455	36.6094	48.9344	0.4503 (0.2741)	0.5261 (0.3084)	0.0639 (0.0518)	0.0686
SD	25.3166	31.9669	8.1981	10.9098	20.1288	33.8452	0.4651	0.6117	0.0597	0.0609
Supplements	Cadmium		Chromium		Cobalt		Copper		Indium	
S1	0.0009	0.0012	0.0237	0.0316	0.0035	0.0047	0.0037	0.0050	0.0001	0.0001
S2	0.0002	0.0002	0.0052	0.0052	0.0012	0.0012	0.0075	0.0075	0.0003	0.0003
S3	0.0007	0.0010	0.0129	0.0172	0.0040	0.0054	0.0070	0.0093	0.0000	0.0000
S4	0.0002	0.0002	0.0034	0.0034	0.0023	0.0023	0.0191	0.0191	0.0002	0.0002
S5	0.0007	0.0007	0.1451	0.1451	0.0021	0.0021	0.0131	0.0131	0.0001	0.0001
S6	0.0004	0.0004	0.0611	0.0611	0.0011	0.0011	0.0042	0.0042	0.0001	0.0001
S7	0.0003	0.0003	0.0045	0.0045	0.0006	0.0006	0.0014	0.0014	0.0000	0.0000
S8 (>11 years)	0.0004	0.0005	0.0059	0.0074	0.0009	0.0012	0.0037	0.0046	0.0000	0.0000
S8 (4–10 years)	0.0001	0.0002	0.0022	0.0029	0.0003	0.0005	0.0014	0.0018	0.0000	0.0000
Mean (Median)	0.0006 (0.0003)	0.0006 (0.0004)	0.0327 (0.0094)	0.0344 (0.0123)	0.0027 (0.014)	0.0030 (0.0014)	0.0085 (0.0056)	0.0096	0.0001 (0.0001)	0.0001 (0.0001)
SD	0.0006	0.0006	0.0493	0.0488	0.0034	0.0034	0.0077	0.0094	0.0001	0.0001
Supplements	Iron		Lead		Manganese		Nickel		Silver	
S1	4.4035	5.8713	0.0038	0.0051	0.2017	0.2690	0.0237	0.0316	0.0079	0.0105
S2	1.2748	1.2748	0.0007	0.0007	0.0795	0.0795	0.0072	0.0072	0.0092	0.0092
S3	1.1756	1.5674	0.0001	0.0001	0.0746	0.0994	0.1479	0.1972	0.0016	0.0021
S4	1.1695	1.1695	0.0014	0.0014	0.1903	0.1903	0.0090	0.0090	0.0001	0.0001
S5	4.0332	4.0332	0.0021	0.0021	0.1495	0.1495	0.0628	0.0628	0.0001	0.0001
S6	1.7776	1.7776	0.0022	0.0022	0.1029	0.1029	0.0113	0.0113	0.0001	0.0001
S7	0.2678	0.2678	0.0003	0.0003	0.0219	0.0219	0.0131	0.0131	0.0005	0.0005
S8 (>11 years)	0.6565	0.8206	0.0006	0.0008	0.0441	0.0551	0.0152	0.0191	0.0033	0.0041
S8 (4–10 years)	0.2462	0.3282	0.0002	0.0003	0.0165	0.0221	0.0057	0.0076	0.0012	0.0017

Table 3 (continued)

Mean (Median)	1.8472	2.1057	0.0012 (0.0008)	0.0015 (0.0009)	0.1143	0.1330	0.0643 (0.0142)	0.0662 (0.0163)	0.0032 (0.0019)	0.0036 (0.0023)
SD	1.4580	1.8268	0.0012	0.0016	0.0790	0.1034	0.1340	0.1333	0.0037	0.0042
Supplements	Titanium		Zinc							
S1	0.0003	0.0005	0.0483	0.0644						
S2	0.0002	0.0002	0.0204	0.0204						
S3	0.0004	0.0006	0.0186	0.0248						
S4	0.0000	0.0000	0.0949	0.0949						
S5	0.0003	0.0003	0.3083	0.3083						
S6	0.0003	0.0003	0.0745	0.0745						
S7	0.0001	0.0001	0.0149	0.0149						
S8 (>11 years)	0.0001	0.0002	0.0425	0.0531						
S8 (4–10 years)	0.0001	0.0001	0.0159	0.0212						
Mean (Median)	0.0003 (0.0002)	0.0003 (0.0002)	0.0673 (0.0454)	0.0751 (0.513)						
SD	0.0004	0.0004	0.0684	0.0712						

A: Average recommended daily dose (g) and B: maximum daily dose specified on the labels (g). SD: Standard deviation. Median values are given in parentheses for non-parametric variables. S8 supplementation values for 4–10 years are not included in the mean and SD calculations

mg kg⁻¹ in sample S2. Similarly, the nickel content in S3 was 65.75 mg kg⁻¹, in stark contrast to 1.45 mg kg⁻¹ in S2. Moreover, the calcium concentration in sample S8 was nearly 75 times higher than that in S2.

These findings highlight the importance of regular heavy metal and macro mineral analyses for Spirulina supplements. To ensure public health and safety, it is imperative that manufacturers perform these analyses systematically, provide accurate labeling of elemental concentrations, and share the results transparently with consumers. Such measures would help mitigate potential health risks and foster consumer trust in the safety and quality of Spirulina products.

The maximum permissible levels in food supplements for individuals over 11 years of age are as follows: calcium (1500 mg day⁻¹), magnesium (250 mg day⁻¹), potassium (1500 mg day⁻¹), iron (17 mg day⁻¹), manganese (2 mg day⁻¹), boron (8 mg day⁻¹), copper (2 mg day⁻¹), molybdenum (0.35 mg day⁻¹), zinc (15 mg day⁻¹), cadmium (3 mg kg⁻¹), and lead (3 mg kg⁻¹) (European Commission Regulation 2023; Republic of Turkey 2013; 2023).

The tolerable upper intake levels for adults are slightly higher and include: calcium (2500 mg day⁻¹), magnesium (250–300 mg day⁻¹), iron (45 mg day⁻¹), manganese (8–11 mg day⁻¹), boron (10–20 mg day⁻¹), copper (5–10 mg day⁻¹), molybdenum (0.6–2.6 mg day⁻¹), zinc (25–40 mg day⁻¹), and nickel (1 mg day⁻¹) (Food and Nutrition Board 2019a; EFSA 2024).

It is noteworthy that Neher et al. (2018) reported that cadmium levels in 11 Spirulina supplements exceeded the FDA's maximum limits, highlighting the importance of strict monitoring and regulation of such products.

Furthermore, Rzymiski et al. (2019) reported that among 13 Spirulina-containing and 10 *Chlorella*-containing supplement products, the aluminum levels in five products exceeded the tolerable weekly intake (TWI), and the lead levels in ten products surpassed the limits established by the European Union (EU) Commission.

In the present study, based on the maximum daily doses (mg day⁻¹) specified on the labels of Spirulina supplements (Table 3), none of the products exceeded the permissible limits for heavy metals and macrominerals as defined by the Republic of Türkiye, Ministry of Food, Agriculture and Livestock (2013), the Food and Nutrition Board (2019b), the Republic of Türkiye, Ministry of Health, General Directorate of Public Health (2022), the European Union Commission Regulation (2023), the Republic of Turkey, Ministry of Food, Agriculture and Livestock (2023) or the European Food and Safety Authority (EFSA) (2024).

The TWI level of aluminum for a 70 kg individual is 70 mg week⁻¹ (EFSA 2008). Among the supplements tested, the highest aluminum content was observed in sample S1, which, when consumed at the maximum recommended dose,

Table 4 EDI and CDI levels of heavy metals caused Spirulina supplements in different age groups and pregnant and breastfeeding women

Supplements	Element	Chronic Daily Intake												
		Estimated Daily Intake					Pregnant and Breastfeeding Women							
		Age (years)		Age (years)		Age (years)		Age (years)		Age (years)				
		≥21	16 to <21	11 to <16	6 to <11	2 to <6	≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women		
S1	Al	0.0242	0.0270	0.0340	0.0608	0.1111	0.0265	0.0211	0.0264	0.0419	0.1338	0.4468	0.0254	
	Pb	0.0001	0.0001	0.0001	0.0002	0.0003	0.0001	0.0001	0.0001	0.0001	0.0004	0.0012	0.0001	
	Cd	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0003	0.0000	
	Cr	0.0004	0.0004	0.0006	0.0010	0.0018	0.0004	0.0003	0.0004	0.0007	0.0022	0.0073	0.0004	
	B	0.0014	0.0016	0.0020	0.0036	0.0065	0.0015	0.0012	0.0015	0.0025	0.0078	0.0261	0.0015	
	Co	0.0001	0.0001	0.0001	0.0001	0.0003	0.0001	0.0001	0.0001	0.0001	0.0003	0.0011	0.0001	
	Cu	0.0001	0.0001	0.0001	0.0002	0.0003	0.0001	0.0001	0.0001	0.0001	0.0003	0.0012	0.0001	
	Fe	0.0734	0.0820	0.1034	0.1846	0.3374	0.0804	0.0642	0.0802	0.1274	0.4064	1.3575	0.0771	
	Mn	0.0034	0.0038	0.0047	0.0085	0.0155	0.0037	0.0029	0.0037	0.0058	0.0186	0.0622	0.0035	
	Ni	0.0004	0.0004	0.0006	0.0010	0.0018	0.0004	0.0003	0.0004	0.0007	0.0022	0.0073	0.0004	
	Ag	0.0001	0.0001	0.0002	0.0003	0.0006	0.0001	0.0001	0.0001	0.0002	0.0007	0.0024	0.0001	
	Zn	0.0008	0.0009	0.0011	0.0020	0.0037	0.0009	0.0007	0.0009	0.0014	0.0045	0.0149	0.0008	
	S2	Al	0.0016	0.0018	0.0023	0.0040	0.0074	0.0018	0.0014	0.0017	0.0028	0.0089	0.0296	0.0017
		Pb	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000
Cd		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Cr		0.0001	0.0001	0.0001	0.0002	0.0003	0.0001	0.0001	0.0001	0.0001	0.0004	0.0012	0.0001	
B		0.0024	0.0027	0.0034	0.0060	0.0110	0.0026	0.0021	0.0026	0.0041	0.0132	0.0441	0.0025	
Co		0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0003	0.0000	
Cu		0.0001	0.0001	0.0001	0.0002	0.0004	0.0001	0.0001	0.0001	0.0002	0.0005	0.0017	0.0001	
Fe		0.0159	0.0178	0.0224	0.0401	0.0733	0.0175	0.0139	0.0174	0.0277	0.0882	0.2947	0.0167	
Mn		0.0010	0.0011	0.0014	0.0025	0.0046	0.0011	0.0009	0.0011	0.0017	0.0055	0.0184	0.0010	
Ni		0.0001	0.0001	0.0001	0.0002	0.0004	0.0001	0.0001	0.0001	0.0002	0.0005	0.0017	0.0001	
Ag		0.0001	0.0001	0.0002	0.0003	0.0005	0.0001	0.0001	0.0001	0.0002	0.0006	0.0021	0.0001	
Zn		0.0003	0.0003	0.0004	0.0006	0.0012	0.0003	0.0002	0.0003	0.0004	0.0014	0.0047	0.0003	

Table 4 (continued)

Supplements	Element	Estimated Daily Intake					Chronic Daily Intake							
		Age (years)					Age (years)							
		≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	
S3	Al	0.0034	0.0038	0.0048	0.0086	0.0157	0.0038	0.0030	0.0037	0.0059	0.0190	0.0633	0.0036	
	Pb	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Cd	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0004	0.0000	
	Cr	0.0018	0.0020	0.0026	0.0046	0.0083	0.0020	0.0016	0.0020	0.0031	0.0100	0.0335	0.0019	
	B	0.0010	0.0011	0.0014	0.0025	0.0046	0.0011	0.0009	0.0011	0.0017	0.0055	0.0184	0.0010	
	Co	0.0001	0.0001	0.0002	0.0003	0.0006	0.0001	0.0001	0.0001	0.0002	0.0007	0.0025	0.0001	
	Cu	0.0002	0.0003	0.0003	0.0006	0.0011	0.0003	0.0002	0.0003	0.0004	0.0013	0.0043	0.0002	
	Fe	0.0392	0.0438	0.0552	0.0986	0.1802	0.0429	0.0343	0.0428	0.0680	0.2170	0.7248	0.0412	
	Mn	0.0025	0.0028	0.0035	0.0063	0.0114	0.0027	0.0022	0.0027	0.0043	0.0138	0.0460	0.0026	
	Ni	0.0049	0.0055	0.0069	0.0124	0.0227	0.0054	0.0043	0.0054	0.0086	0.0273	0.0912	0.0052	
	Ag	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0000	0.0001	0.0001	0.0003	0.0010	0.0001	
	Zn	0.0006	0.0007	0.0009	0.0016	0.0028	0.0007	0.0005	0.0007	0.0011	0.0034	0.0115	0.0007	
	S4	Al	0.0027	0.0030	0.0038	0.0069	0.0125	0.0030	0.0024	0.0030	0.0047	0.0151	0.0504	0.0029
		Pb	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0005	0.0000
Cd		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	
Cr		0.0002	0.0002	0.0003	0.0005	0.0010	0.0002	0.0002	0.0002	0.0004	0.0012	0.0040	0.0002	
B		0.0002	0.0002	0.0002	0.0004	0.0008	0.0002	0.0002	0.0002	0.0003	0.0010	0.0033	0.0002	
Co		0.0000	0.0000	0.0001	0.0001	0.0002	0.0000	0.0000	0.0000	0.0001	0.0002	0.0008	0.0000	
Cu		0.0004	0.0004	0.0005	0.0009	0.0016	0.0004	0.0003	0.0004	0.0006	0.0020	0.0066	0.0004	
Fe		0.0218	0.0244	0.0307	0.0549	0.1003	0.0239	0.0191	0.0238	0.0379	0.1208	0.4036	0.0229	
Mn		0.0036	0.0040	0.0050	0.0089	0.0163	0.0039	0.0031	0.0039	0.0062	0.0197	0.0657	0.0037	
Ni		0.0002	0.0002	0.0002	0.0004	0.0008	0.0002	0.0001	0.0002	0.0003	0.0009	0.0031	0.0002	
Ag		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Zn		0.0018	0.0020	0.0025	0.0045	0.0081	0.0019	0.0015	0.0019	0.0031	0.0098	0.0328	0.0019	

Table 4 (continued)

Supplements	Element	Estimated Daily Intake					Chronic Daily Intake					
		Age (years)					Age (years)					
		≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	≥21	16 to <21	11 to <16	6 to <11	2 to <6
S5	Al	0.0102	0.0114	0.0144	0.0257	0.0470	0.0112	0.0178	0.0567	0.1893	0.0108	
	Pb	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0003	0.0000	
	Cd	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	
	Cr	0.0008	0.0009	0.0011	0.0019	0.0035	0.0008	0.0013	0.0042	0.0141	0.0008	
	B	0.0010	0.0011	0.0014	0.0024	0.0045	0.0011	0.0017	0.0054	0.0180	0.0010	
	Co	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0004	0.0000	
	Cu	0.0001	0.0001	0.0002	0.0003	0.0005	0.0001	0.0002	0.0007	0.0022	0.0001	
	Fe	0.0363	0.0406	0.0511	0.0913	0.1669	0.0398	0.0630	0.2010	0.6714	0.0381	
	Mn	0.0013	0.0015	0.0019	0.0034	0.0062	0.0015	0.0023	0.0074	0.0249	0.0014	
	Ni	0.0006	0.0006	0.0008	0.0014	0.0026	0.0006	0.001	0.0031	0.0105	0.0006	
	Ag	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Zn	0.0028	0.0031	0.0039	0.0070	0.0128	0.0030	0.0048	0.0154	0.0513	0.0029	
	S6	Al	0.0051	0.0057	0.0071	0.0127	0.0233	0.0055	0.0088	0.0280	0.0936	0.0053
		Pb	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0002	0.0000
Cd		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Cr		0.0000	0.0000	0.0001	0.0001	0.0002	0.0000	0.0001	0.0002	0.0008	0.0000	
B		0.0003	0.0003	0.0004	0.0007	0.0013	0.0003	0.0005	0.0016	0.0053	0.0003	
Co		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	
Cu		0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0001	0.0004	0.0000	
Fe		0.0103	0.0116	0.0146	0.0260	0.0475	0.0113	0.0179	0.0573	0.1912	0.0109	
Mn		0.0006	0.0007	0.0008	0.0015	0.0028	0.0007	0.0010	0.0033	0.0111	0.0006	
Ni		0.0001	0.0001	0.0001	0.0002	0.0003	0.0001	0.0001	0.0004	0.0012	0.0001	
Ag		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Zn		0.0004	0.0005	0.0006	0.0011	0.0020	0.0005	0.0008	0.0024	0.0080	0.0005	

Table 4 (continued)

Supplements	Element	Estimated Daily Intake					Chronic Daily Intake						
		Age (years)					Age (years)						
		≥21	16 to <16	11 to <11	6 to <6	2 to <2	≥21	16 to <16	11 to <11	6 to <6	2 to <2	Pregnant and Breastfeeding Women	
S7	Al	0.0008	0.0009	0.0011	0.0019	0.0035	0.0008	0.0008	0.0013	0.0042	0.0141	0.0008	
	Pb	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	
	Cd	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Cr	0.0000	0.0000	0.0001	0.0001	0.0002	0.0000	0.0000	0.0001	0.0002	0.0007	0.0000	
	B	0.0002	0.0002	0.0002	0.0004	0.0007	0.0002	0.0002	0.0003	0.0009	0.0030	0.0002	
	Co	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	
	Cu	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0001	0.0002	0.0000	
	Fe	0.0023	0.0025	0.0032	0.0057	0.0105	0.0020	0.0025	0.0039	0.0126	0.0421	0.0024	
	Mn	0.0002	0.0002	0.0003	0.0005	0.0009	0.0002	0.0002	0.0003	0.0010	0.0034	0.0002	
	Ni	0.0001	0.0001	0.0002	0.0003	0.0005	0.0001	0.0001	0.0002	0.0006	0.0021	0.0001	
	Ag	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	
	Zn	0.0001	0.0001	0.0002	0.0003	0.0006	0.0001	0.0001	0.0002	0.0007	0.0023	0.0001	
	S8	Al	0.0043	0.0048	0.0060	0.0043	0.0079	0.0038	0.0047	0.0074	0.0095	0.0317	0.0045
		Pb	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000
Cd		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Cr		0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0002	0.0002	0.0007	0.0001	
B		0.0004	0.0004	0.0006	0.0004	0.0007	0.0004	0.0004	0.0007	0.0009	0.0030	0.0004	
Co		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	
Cu		0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004	0.0001	
Fe		0.0103	0.0115	0.0144	0.0103	0.0189	0.0090	0.0112	0.0178	0.0227	0.0759	0.0108	
Mn		0.0007	0.0008	0.0010	0.0007	0.0013	0.0006	0.0008	0.0012	0.0015	0.0051	0.0007	
Ni		0.0002	0.0003	0.0003	0.0002	0.0004	0.0002	0.0003	0.0004	0.0005	0.0018	0.0003	
Ag		0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0004	0.0001	
Zn		0.0007	0.0007	0.0009	0.0007	0.0012	0.0006	0.0007	0.0012	0.0015	0.0049	0.0007	

Levels higher than the RFD are in bold

Table 5 THQ and HI of heavy metals caused Spirulina supplements in different age groups and pregnant and breastfeeding women

<i>Supplements</i>	Element	Target Hazard Quotient						Hazard Index						
		Age (years)						Age (years)						
		≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	
<i>S1</i>	Al	0.0211	0.0264	0.0419	0.1338	0.4468	0.0254	0.4620	0.5767	0.9165	2.9241	9.7667	0.5549	
	Pb	0.0159	0.0199	0.0316	0.1009	0.3369	0.0191							
	Cd	0.0263	0.0328	0.0521	0.1661	0.5549	0.0315							
	Cr	0.0002	0.0003	0.0005	0.0015	0.0049	0.0003							
	B	0.0618	0.0771	0.1226	0.3911	1.3063	0.0742							
	Co	0.1714	0.2139	0.3399	1.0845	3.6222	0.2058							
	Cu	0.0014	0.0017	0.0027	0.0087	0.0289	0.0016							
	Fe	0.1003	0.1253	0.1990	0.6350	2.1211	0.1205							
	Mn	0.0210	0.0262	0.0417	0.1330	0.4442	0.0252							
	Ni	0.0173	0.0216	0.0343	0.1094	0.3653	0.0208							
	Ag	0.0230	0.0287	0.0456	0.1454	0.4855	0.0276							
	Zn	0.0023	0.0029	0.0047	0.0149	0.0496	0.0028							
	<i>S2</i>	Al	0.0014	0.0018	0.0028	0.0089	0.0296	0.0017	0.2469	0.3082	0.4898	1.5625	5.2188	0.2965
		Pb	0.0020	0.0025	0.0040	0.0129	0.0429	0.0024						
		Cd	0.0033	0.0041	0.0065	0.0208	0.0694	0.0039						
		Cr	0.0000	0.0000	0.0001	0.0002	0.0008	0.0000						
		B	0.1043	0.1302	0.2069	0.6602	2.2051	0.1253						
Co		0.0438	0.0546	0.0868	0.2769	0.9248	0.0525							
Cu		0.0021	0.0026	0.0041	0.0130	0.0434	0.0025							
Fe		0.0218	0.0272	0.0432	0.1379	0.4605	0.0262							
Mn		0.0435	0.0543	0.0863	0.2753	0.9196	0.0522							
Ni		0.0040	0.0050	0.0079	0.0251	0.0838	0.0048							
Ag	0.0200	0.0250	0.0397	0.1267	0.4231	0.0240								
Zn	0.0007	0.0009	0.0015	0.0047	0.0157	0.0009								

Table 5 (continued)

Supplements	Element	Target Hazard Quotient					Hazard Index							
		Age (years)					Age (years)							
		≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	
S3	Al	0.0030	0.0037	0.0059	0.0190	0.0633	0.0036	0.8736	1.0905	1.7329	5.5286	18.4660	1.0491	
	Pb	0.0006	0.0007	0.0011	0.0036	0.0119	0.0007							
	Cd	0.0420	0.0524	0.0833	0.2658	0.8878	0.0504							
	Cr	0.0011	0.0013	0.0021	0.0067	0.0224	0.0013							
	B	0.0435	0.0544	0.0864	0.2756	0.9204	0.0523							
	Co	0.3894	0.4861	0.7724	2.4643	8.2309	0.4676							
	Cu	0.0051	0.0064	0.0101	0.0323	0.1079	0.0061							
	Fe	0.0536	0.0669	0.1063	0.3391	1.1325	0.0643							
	Mn	0.1087	0.1358	0.2157	0.6882	2.2987	0.1306							
	Ni	0.2157	0.2693	0.4280	1.3654	4.5605	0.2591							
	Ag	0.0091	0.0113	0.0180	0.0573	0.1914	0.0109							
	Zn	0.0018	0.0023	0.0036	0.0114	0.0382	0.0022							
	S4	Al	0.0024	0.0030	0.0047	0.0151	0.0504	0.0029	0.3544	0.4424	0.7030	2.2429	7.4915	0.4256
		Pb	0.0068	0.0084	0.0134	0.0427	0.1427	0.0081						
Cd		0.0079	0.0098	0.0156	0.0498	0.1665	0.0095							
Cr		0.0001	0.0002	0.0002	0.0008	0.0027	0.0002							
B		0.0077	0.0097	0.0154	0.0490	0.1637	0.0093							
Co		0.1236	0.1543	0.2452	0.7822	2.6126	0.1484							
Cu		0.0078	0.0098	0.0155	0.0495	0.1653	0.0094							
Fe		0.0298	0.0372	0.0592	0.1888	0.6306	0.0358							
Mn		0.1554	0.1940	0.3082	0.9833	3.2843	0.1866							
Ni		0.0074	0.0092	0.0146	0.0465	0.1554	0.0088							
Ag	0.0004	0.0005	0.0008	0.0025	0.0083	0.0005								
Zn	0.0052	0.0064	0.0102	0.0327	0.1092	0.0062								

Table 5 (continued)

Supplements	Element	Target Hazard Quotient					Hazard Index							
		Age (years)					Age (years)							
		≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	
S5	Al	0.0090	0.0112	0.0178	0.0567	0.1893	0.0108	0.2677	0.3343	0.5311	1.6945	5.6599	0.3216	
	Pb	0.0046	0.0057	0.0091	0.0290	0.0970	0.0055							
	Cd	0.0104	0.0130	0.0206	0.0658	0.2197	0.0125							
	Cr	0.0004	0.0006	0.0009	0.0028	0.0094	0.0005							
	B	0.0426	0.0532	0.0845	0.2696	0.9004	0.0512							
	Co	0.0567	0.0708	0.1125	0.3588	1.1986	0.0681							
	Cu	0.0026	0.0032	0.0051	0.0163	0.0544	0.0031							
	Fe	0.0496	0.0620	0.0984	0.3141	1.0491	0.0596							
	Mn	0.0588	0.0735	0.1167	0.3725	1.2440	0.0707							
	Ni	0.0247	0.0309	0.0491	0.1565	0.5229	0.0297							
	Ag	0.0002	0.0002	0.0004	0.0012	0.0040	0.0002							
	Zn	0.0081	0.0101	0.0161	0.0512	0.1711	0.0097							
	S6	Al	0.0044	0.0055	0.0088	0.0280	0.0936	0.0053	0.0875	0.1093	0.1736	0.5540	1.8503	0.1051
		Pb	0.0033	0.0041	0.0065	0.0207	0.0690	0.0039						
Cd		0.0040	0.0049	0.0079	0.0250	0.0837	0.0048							
Cr		0.0000	0.0000	0.0000	0.0002	0.0005	0.0000							
B		0.0125	0.0156	0.0247	0.0790	0.2637	0.0150							
Co		0.0183	0.0229	0.0363	0.1159	0.3873	0.0220							
Cu		0.0005	0.0007	0.0010	0.0033	0.0112	0.0006							
Fe		0.0141	0.0176	0.0280	0.0895	0.2988	0.0170							
Mn		0.0262	0.0327	0.0519	0.1656	0.5533	0.0314							
Ni		0.0029	0.0036	0.0057	0.0182	0.0606	0.0034							
Ag	0.0001	0.0001	0.0002	0.0006	0.0019	0.0001								
Zn	0.0013	0.0016	0.0025	0.0080	0.0267	0.0015								

Table 5 (continued)

Supplements	Element	Target Hazard Quotient					Hazard Index						
		Age (years)					Age (years)						
		≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women	≥21	16 to <21	11 to <16	6 to <11	2 to <6	Pregnant and Breastfeeding Women
S7	Al	0.0007	0.0008	0.0013	0.0042	0.0141	0.0008	0.0440	0.0549	0.0872	0.2784	0.9297	0.0528
	Pb	0.0007	0.0009	0.0014	0.0045	0.0152	0.0009						
	Cd	0.0039	0.0049	0.0078	0.0249	0.0832	0.0047						
	Cr	0.0000	0.0000	0.0000	0.0001	0.0005	0.0000						
	B	0.0070	0.0088	0.0139	0.0444	0.1482	0.0084						
	Co	0.0142	0.0178	0.0282	0.0900	0.3006	0.0171						
	Cu	0.0003	0.0003	0.0005	0.0017	0.0057	0.0003						
	Fe	0.0031	0.0039	0.0062	0.0197	0.0657	0.0037						
	Mn	0.0081	0.0101	0.0161	0.0514	0.1718	0.0098						
	Ni	0.0049	0.0061	0.0096	0.0307	0.1027	0.0058						
	Ag	0.0007	0.0008	0.0013	0.0043	0.0143	0.0008						
	Zn	0.0004	0.0005	0.0007	0.0023	0.0078	0.0004						
S8	Al	0.0038	0.0047	0.0074	0.0095	0.0317	0.0045	0.1431	0.1786	0.2838	0.3621	1.2096	0.1718
	Pb	0.0025	0.0031	0.0050	0.0063	0.0211	0.0030						
	Cd	0.0104	0.0130	0.0206	0.0263	0.0879	0.0125						
	Cr	0.0001	0.0001	0.0001	0.0001	0.0005	0.0001						
	B	0.0176	0.0219	0.0348	0.0444	0.1484	0.0211						
	Co	0.0419	0.0523	0.0832	0.1061	0.3545	0.0504						
	Cu	0.0013	0.0016	0.0025	0.0032	0.0106	0.0015						
	Fe	0.0140	0.0175	0.0278	0.0355	0.1186	0.0168						
	Mn	0.0302	0.0377	0.0598	0.0764	0.2550	0.0362						
	Ni	0.0104	0.0130	0.0207	0.0264	0.0881	0.0125						
	Ag	0.0091	0.0113	0.0180	0.0230	0.0768	0.0109						
	Zn	0.0019	0.0024	0.0038	0.0049	0.0164	0.0023						

Target Hazard Quotient and Hazard Index levels greater than 1 are in bold

Table 6 The minimum and maximum heavy metals and macro minerals content (mg kg⁻¹) of Spirulina supplements in some studies

References	Neher et al. 2018	Ryzmski et al. 2019	Al-Dhabi 2013	Muys et al. 2019	Janda-Milczarek et al. 2023	This Study
Analytical method	MPAES	ICP-OES	ICP-MS	ICP-MS	ICP-OES	ICP-MS
Sample size	11	13	25	11	33	8
Calcium	34.94–454.05.94.05	2,200–119,300	Na	Na	761.191–76.191,781.53	516.28–38.28,759.30
Magnesium	11–2,311	1,900–6,600	0.002–0.042.002.042	Na	2,134.017–11.017,067.04	1,757.03–6.03,266.08
Potassium	<LOD–18,756	8,500–20,900	Na	Na	9,019.566–38.566,335.28	8,211.03–14.03,336.84
Aluminum	<LOD–1,270.02	2,155.6 ± 1,774.7 (1299.8)	Na	Na	Na	25.63–201.51.63.51
Sodium	5.25–798.06.25.06	4,200–28,100	Na	Na	3,102.046–36.046,144.06	Na
Phosphorus	<LOD ± 11,539	6,600–58,700	Na	Na	7,196.181–70.181,759.49	Na
Boron	Na	Na	Na	Na	Na	4.72–38.15.72.15
Cadmium	<LOQ–2.14	0.125 ± 0.055 (0.128)	Na	0.01–0.17.01.17	Na	0.03–0.32.03.32
Chromium	<LOD–3.74	0.6–24.4.6.4	Na	2.1–22.3.1.3	Na	1.04–24.18.04.18
Cobalt	Na	0.08–9.4.08.4	Na	Na	Na	0.24–1.78.24.78
Copper	<LOD–832.26	0.9–15.1.9.1	Na	0.94–6.4.94.4	Na	0.50–9.53.50.53
Indium	Na	Na	Na	Na	Na	0.01–0.08.01.08
Iron	<LOD–905.8	368.5–2.5,286.6	Na	Na	212.23–2.23,785.82	181.9–672.21.9.21
Lead	Na	2.6 ± 1.9 (2.3)	Na	Nd	Na	0.03–0.72.03.72
Manganese	<LOD–119	26.1–109.8	0.005–2.248.005.248	Na	Na	14.86–94.70.86.70
Mercury	Na	Na	0.002–0.028.002.028	0.02–0.11.02.11	Na	Na
Molybdenum	Na	0.09–0.90	Na	Na	Na	Na
Nickel	<LOQ–8.91	1.52 ± 0.72 (1.33)	0.211–4.672.211.672	1.1–3.4.1.4	Na	1.45–65.75.45.75
Platin	Na	Na	0.001–0.012.001.012	Na	Na	Na
Selenium	Na	0.0–1.6	Na	Na	0.031–5.69.031.69	Na
Silver	Na	Na	Na	Na	Na	0.02–1.83.02.83
Titanium	Na	Na	Na	Na	Na	0.02–0.19.02.19
Zinc	<LOQ–8,928	9.6–61.4	0.533–6.225.533.225	17–50	7.068–322.14.068.14	4.08–51.38.08.38

ICP-OES: Inductively Coupled Plasma-Optical Emission Spectrometry, ICP-MS: Inductively Coupled Plasma-Mass Spectrometry, MPAES: Microwave Induced Plasma Atomic Emission Spectrometry, Na: not analyzed. ^aStandard deviations from the study were not added to this table. <LOD values found below the detection limit, <LOQ values found below the quantification limit. ^bThe values given in g kg⁻¹ in the study were converted to mg kg⁻¹. Different analysis methods were applied for arsenic and chromium. The mean and SD of some values are given and their medians are in parentheses. ^cThe authors have given the results based on dry weight

contributes 13.53 mg to the weekly aluminum intake. Consequently, none of the supplements analyzed in this study exceeded the tolerable intake levels for aluminum or any other heavy metals and macrominerals.

The THQ is an integrated risk index that compares the amount of a contaminant ingested to a standard reference dose. A THQ of less than 1 indicates that the exposure level

is below the reference dose, which assumes that daily exposure at this level is unlikely to cause adverse health effects in a human population over a lifetime. To assess the health risk from combined exposure to multiple chemicals over a lifetime, THQs are summed to calculate HI values. HI values > 1 indicate that non-carcinogenic health effects are likely to occur (Adebiyi et al. 2019). This study assessed the potential

health risks associated with heavy metal content in Spirulina supplements, using HI values derived from a health risk assessment. For individuals aged 21 and older, the results indicate that the heavy metal content in the examined Spirulina supplements does not pose a non-carcinogenic health risk. Additionally, S7 supplementation was found to be safe across all age groups, including pregnant and breastfeeding women, and its consumption does not present a potential health concern. It should be noted that supplement S7 is not a pure Spirulina product, as it contains additional ingredients, including kelp, nettle, and tricalcium phosphate. This compositional difference may affect the elemental profile and could contribute to the relatively lower heavy metal levels observed in this sample. Therefore, the results for S7 should be interpreted with caution, as the measured values may not solely reflect the characteristics of Spirulina.

In contrast, the HI value for the S3 supplement exceeded 1 in all age groups, including pregnant and breastfeeding women, except for adults. Thus, consumption of S3 may represent a potential health risk for these populations. However, the label of this supplement does not include any specific age-related usage recommendations, which may increase the risk of inappropriate consumption. S3 consistently exhibited the highest HI values and the highest levels of cadmium, chromium, nickel, and cobalt across most groups. Notably, S3 is a locally produced product; however, other samples produced in Türkiye (S4, S7, and S8) did not show such high levels of contamination. Possible reasons may include differences in water quality, environmental exposure, or variations in cultivation conditions such as processing practices. Since spirulina is known to accumulate metals from its growing medium, contamination may be influenced by local production conditions (Muys et al. 2019). These findings highlight the importance of rigorous quality control and monitoring during cultivation and processing to ensure product safety.

For the 2- to < 6-year-old age group, all supplements except S7 had HI values exceeding 1, indicating a potential health risk. Similarly, in the 6- to <11 age group, HI values > 1 were observed in five supplements (S1, S2, S3, S4, S5). Among the 16 to <21 and 11 to <16 age groups, only the S3 supplement showed an HI value greater than 1. These findings highlight the importance of clearly labeling Spirulina supplements with appropriate age-related usage recommendations to mitigate potential health risks.

As indicated in Table 1, S1 and S2 are available as powders and can be obtained from local markets. However, their labels lack any statements specifying that they are intended for adults or providing age-related usage recommendations. As shown in Table 5, this lack of guidance poses a potential risk to children under 11, as the HI value for these supplements was calculated to exceed 1 for this age group.

Although the label for the S8 supplement recommends 1–2 tablets for children aged 4–10 years, our calculations indicate that it may pose a non-carcinogenic health risk for children aged 2 to <6 years, with an HI value of 1.2096.

Currently, no standardized guidelines exist in the literature specifying the recommended daily intake or maximum allowable dose for Spirulina consumption. Nevertheless, powdered Spirulina is readily available in markets, allowing individuals to purchase it in unlimited quantities for culinary use, often adding it to meals without restriction. This practice raises concerns about potential public health risks, highlighting the need for further investigation into whether such unregulated usage may be harmful. Regular monitoring of Spirulina and other algae-based products consumed as dietary supplements in gram-level doses is crucial to ensure they do not contain harmful substances (Grosshagauer et al. 2020).

Although data on long-term Spirulina consumption exceeding the recommended daily dose and its potential consequences are limited, several notable cases have been documented. Seo et al. (2023) reported the case of a 79-year-old man who developed pemphigus foliaceus after prolonged excessive consumption of Spirulina. Despite a recommended daily dose of 4 g, the patient had been consuming 20 g per day for the past seven months. Histopathological examination confirmed the diagnosis, and the patient's condition improved following discontinuation of Spirulina and initiation of immunosuppressive therapy.

Similarly, previous studies have highlighted cases where Spirulina consumption was associated with autoimmune skin disorders (Bax et al. 2021). These observations emphasize the need for further research to explore the potential risks associated with long-term and excessive use of Spirulina and other algae-based dietary supplements. Such studies would provide valuable insights into the underlying mechanisms and help establish safety guidelines for their consumption.

The contribution of Spirulina supplements to daily dietary reference values was calculated in our study using the recommended average doses listed on their labels. These calculations were conducted separately using the EFSA Dietary Reference Values for Nutrients Summary Report (2017), the Food and Nutrition Board's Committee to Review the Dietary Reference Intakes (2019b), and the Republic of Türkiye, Ministry of Health, General Directorate of Public Health (2022).

Our findings indicate that Spirulina makes a particularly significant contribution to daily mineral intake, especially for iron, manganese, magnesium, potassium, and calcium (Table 7). However, boron, despite the lack of an established recommended daily allowance, was found to contribute approximately 3.3% to daily intake (Kuru et al. 2018).

In this study, we demonstrated that Spirulina contributes to the daily intake of several essential minerals, including

Table 7 The daily dietary reference values are met percentages of Spirulina supplements in our study

	Male	Female
Magnesium	3.8 ^a , 3.19 ^b , 3.72 ^c	4.5 ^a , 4.32 ^b , 4.46 ^c
Potassium	0.9 ^a , 1.27 ^b , 1.24 ^c	0.9 ^a , 1.66 ^b , 1.24 ^c
Calcium ^d	1.6 ^a , 1.56 ^{b,c}	1.6 ^a , 1.56 ^{b,c}
Iron ^e	16.8 ^a , 23.09 ^b , 16.79 ^c	16.8 ^a , 10.26 ^b , 11.54 ^c
Copper	0.5 ^a , 0.53 ^c	0.7 ^a , 0.65 ^c
Zinc	0.4–0.7.4.7 ^{a,c*} , 0.61 ^b	0.5–0.9.5.9 ^{a,c*} , 0.84 ^b
Manganese	4.97 ^b , 3.81 ^c	6.35 ^b , 3.81 ^c

Values are given in %. ^aPopulation reference intakes and adequate intakes for minerals, for 18–70 years [34], ^bRecommended dietary allowances and adequate intakes, elements, for 19–50 years (Food and Nutrition Board 2019a), ^cPopulation reference intakes and adequate intakes for minerals, for ≥18 years (EFSA 2017), ^d ≥25 years: %1.6 (EFSA 2017; Republic of Türkiye 2022), ^e for post menopause women: %16.8 (EFSA 2017; Republic of Türkiye 2022), ^{a,c*} It varies depending on daily phytate intake

iron, manganese, magnesium, potassium, calcium, and boron. Furthermore, none of the Spirulina supplements examined in this study exceeded the established Dietary Reference Intake (DRI) levels or the Codex limits for heavy metals and macro minerals. However, these findings should not overshadow Spirulina's well-documented ability to bind heavy metals. Based on our health risk assessment, we recommend conducting routine heavy metal analyses on Spirulina supplements. Additionally, product labels should specify age-related usage guidelines and explicitly indicate recommended intake levels, considering potential heavy metal exposure across age groups.

Although carcinogenic risk assessment is an important component of heavy metal risk evaluation, it was not included in the main analysis of this study. This is primarily due to the lack of standardized oral cancer slope factors (CSF) for certain elements, particularly lead and cadmium, in authoritative databases such as USEPA IRIS. In addition, considerable variability exists among reported CSF values in the literature, which may lead to different risk estimates (Alsafran et al. 2021; Mustatea et al. 2021; Oni et al. 2022; California Environmental Protection Agency 2026). This highlights the uncertainty associated with carcinogenic risk assessment for these elements.

Conclusion

This study evaluated the heavy metal and macro-mineral composition of commercially available Spirulina supplements consumed in Türkiye and assessed their potential health risks across different age groups. Although none of the analyzed products exceeded established dietary reference values or regulatory limits for heavy

metals and macro minerals, considerable variability was observed among samples. Notably, one supplement (S3) had HI values exceeding 1 in most age groups, except in adults, indicating a potential non-carcinogenic health risk, particularly for younger individuals. The findings highlight that, despite its well-established nutritional benefits, Spirulina's capacity to accumulate heavy metals may pose safety concerns depending on product source, cultivation conditions, and consumption patterns. Therefore, regular monitoring of heavy metal content in Spirulina supplements is essential. Manufacturers should implement stringent quality control measures during cultivation and processing, ensure transparent reporting of elemental composition, and provide clear labeling, including age-specific consumption recommendations. Furthermore, the lack of standardized guidelines for daily Spirulina intake underscores the need to develop evidence-based regulatory frameworks. This study has some limitations. The number of products analyzed was limited to 8; therefore, the findings may not fully represent all Spirulina supplements available in the Turkish market. However, the selected products reflect those that are commercially available and accessible to consumers, providing an initial insight into potential exposure risks. Future studies should focus on larger sample sizes, batch-to-batch variability, and long-term exposure assessments to better define safe consumption limits and support public health protection.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10811-026-03901-0>.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Özlem Üstün-Aytekin], [Rüya Kuru-Yaşar], [Şahin Yılmaz] and [Fikretin Şahin]. The first draft of the manuscript was written by [Özlem Üstün-Aytekin] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Availability of data and material The authors declare that the data supporting the findings of this study are available within the paper.

Declarations

Conflict of interest/Competing interests The authors have no relevant financial or non-financial interests to disclose.

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