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Assessment of heavy metal concentrations in *Scophthalmus maximus* (Linnaeus, 1758) from the Black Sea coast: Implications for food safety and human health

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ABSTRACT

The present study aimed to investigate the concentrations of heavy metals (Cd, Hg, Pb, Cu, Zn, Fe) in turbot (*Scophthalmus maximus*) samples collected from the Black Sea coast in 2022. The research involved analysing male and female turbot samples for their potential to accumulate these metals and assessing the associated health risks for different age groups (infants, children, adults). Metal analyses were conducted using Inductively Coupled Plasma Mass Spectrophotometry (ICP-MS), and risk assessment was performed using the Hazard Quotient (THQ) and Risk Index (RI) methods.

Results showed that the mean concentrations of heavy metals in both male and female turbots were consistently below the established safety limits set by national and international regulatory authorities. The Estimated Daily Intake (EDI) and THQ values for all metals were found to be well below the corresponding reference doses, indicating no significant noncarcinogenic health risks associated with turbot consumption. Furthermore, the RI values for metals with available Cancer Slope Factors (CSF) were extremely low, suggesting negligible carcinogenic risk from consuming turbot.

Introduction

Heavy metal pollution is a quickly growing problem for water systems, such as oceans, seas, lakes, and rivers in the areas with intensive industry. Increase in metal and pesticides usage together with industrial development reveals heavy metal pollution as an important environmental problem. Nowadays, heavy metals are the primary pollutants of the environment and are one of the most important environmental problems (Kalipci et al., 2010; Aras et al., 2017; Kalipci and Namal, 2018). Heavy metals which have environmental permanence may accumulate biologically in aquatic biota and food chain. For this reason, heavy metals have high toxicity for all living organisms and cause significant health problems since they are not biologically degradable (Ustaoglu and Islam, 2020; Cüce et al., 2022a,b).

The Black Sea is a delicate marine ecosystem facing numerous challenges due to pollutant inputs from coastal countries and major river systems. The Black Sea is contaminated with heavy metals from natural sources (e.g., volcanic activity, weathering of rocks) and anthropogenic activities e.g., industrial discharges, agricultural runoff, urban waste (Bat et al., 2018a). Among these pollutants, heavy metals are of particular concern due to their potential adverse effects on aquatic organisms and human health (Bat, 2017; Bat and Arici, 2018).

Turbot (*Scophthalmus maximus*), a highly sought-after bottom-dwelling fish species (Froese and Pauly, 2023), plays a crucial role in the ecological balance of the Black Sea coastal region. Turbot's ecological significance, coupled with its economic importance (Aydın, 2011; Bat et al., 2013, 2018b; Alkan et al., 2020; Tserkova et al., 2023), necessitates a comprehensive investigation into the potential risks associated with heavy metal accumulation in its tissues. The accumulation of heavy metals in fish tissues is a complex phenomenon influenced by several factors, including water, sediment, and food, and their bioaccumulation in their tissues can have significant ecological and health implications (Bat et al., 2012). Heavy metal accumulations in the edible tissues of turbot in the Black Sea and their effects on human health have been studied for years in the Turkish Black Sea coasts, (Das et al., 2009; Bat et al., 2012, 2017; Mol et al., 2017; Bat et al., 2019; Alkan et al., 2020, 2022a; Kaya Öztürk, 2022) in the Bulgarian Black Sea coasts (Peycheva et al., 2017; Manev et al., 2022) and in the Romanian Black Sea coasts

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(Simionov et al., 2019). In 2022, seafood catches increased by 2.3 % compared to the previous year. In 2022, the amount of sea fish caught was 254,535.3 tonnes and the amount of turbot was 491 tonnes (TÜİK, 2023). Their meat is white, very valuable and high prices (Aydın, 2011). They feed mainly on fish and larger crustaceans and bivalves. It is very good pan fried. Steamed, broiled, boiled, microwaved, and baked are also made (Froese and Pauly, 2023).

In this context, the present study aims to assess the concentrations of six key heavy metals (Cd, Hg, Pb, Cu, Zn, and Fe) in male and female turbot samples collected from the Black Sea coast during the year 2022. The study aims 1) to quantify and compare the levels of Cd, Hg, Pb, Cu, Zn, and Fe in male and female turbot samples, shedding light on potential gender-specific differences in metal accumulation patterns, 2) to identify potential spatial and temporal variations in heavy metal concentrations between turbot samples and among different sampling months, 3) to compare the obtained values with established national and international permissible limits and reference doses to determine the safety of turbot consumption from the Black Sea coast, and 4) to assess the potential health risks associated with consuming turbot contaminated with heavy metals for different age groups (infants, children, adults) based on estimated daily intake (EDI), the target hazard quotient (THQ) and risk index (RI) values.

Therefore, in recent years, the importance and count of studies on ecological health risk assessment have been increasing (Töre et al., 2021; Cüce et al., 2022a,b,c,d; Kalipci et al., 2023).

By achieving these objectives, this study aims to enhance our understanding of heavy metal contamination in turbot from the Black Sea coast and its implications for both environmental health and human well-being. The findings will provide valuable insights for sustainable fisheries management, food safety regulations, and measures to protect the delicate marine ecosystem of the Black Sea.

Materials and methods

Turbot fish were randomly purchased from the local fish market in Samsun, one of the largest cities in the Southern Black Sea region (Fig. 1). Samsun is a large industrial city with intensive agricultural, harbor and fishing activities (Bakan and Büyükgüngör, 2000; Altaş and Büyükgüngör, 2007; Bat et al., 2018a). Turbot is one of the most valuable fish in the Black Sea and is frequently consumed by tourists and local people in this region. Turbots were obtained in January, February, March, September, October, October, November, and December during the open fishing season in 2022. After the length and weight measurements of the fish samples were made, they were placed in clean polyethylene bags and stored at −21 °C until metal analyses. The mean length and weight of turbot were 42±3 cm and 1350±200 g for males, 48±2 cm and 2050±150 g for females, respectively.

Metal analyses

Like the approach employed by Bat et al. (2022b), this study utilized the EPA Method 200.3 for spectrochemical determination of total recoverable elements in biological tissues. Fresh fish meat samples, weighing up to 1.5 g, underwent digestion in Teflon vessels using a mixture of concentrated supra pure grade HNO_3 (65 %) and H_2O_2 (30 %) in a 7:1 ratio. The digestion process was conducted using a microwave digestion system (Milestone SK10 High Pressure Rotor), with adherence to the (HPR-FO-67) temperature and pressure profile for fresh meat. The Teflon bombs containing the samples were subjected to heating at 200 °C for 15 min, followed by an additional 15 min at the same temperature. Subsequently, the digested solution was transferred into 50 mL polypropylene falcon tubes, which were then filled with ultra-pure water. Analysis of elemental concentrations was performed using an Inductively Coupled Plasma Mass Spectrophotometer (ICP-MS, Agilent 7700X). To ensure quality control, certified reference material (Lobster TORT-2) and triplicate measurements were utilized. Calibration curves were generated using standard solutions provided by Agilent (27 element mix: 8500–6940 2A and 8500–6940 Hg), with the analytical precision within 10 %. Throughout the study, a 1 ppm internal standard (Agilent 5188–6525) was consistently employed for sample analysis. Certified values of Cd, Hg, Pb, Cu, Zn and Fe were 26.7, 0.27, 0.35, 106, 180 and 105 mg/kg, respectively. ICP-MS measured values of these metals were 26, 0.28, 0.33, 102, 185 and 101 mg/kg for Cd, Hg, Pb, Cu, Zn and Fe, respectively. The percentage of recovery was calculated between 94.28 % and 103.7 %.

Human health risk assessment

In the present study, health risk indices including the estimated daily intake (EDI) and the estimated weekly intake (EWI) of six metals by humans, target hazard quotient (THQ), total hazard quotient (TTHQ), and carcinogenic risk index (CRI) were assessed.

Estimated daily intake (EDI) and estimated weekly intake (EWI)

The EDI (mg/kg/day) is given by the equation below (Bat et al.,

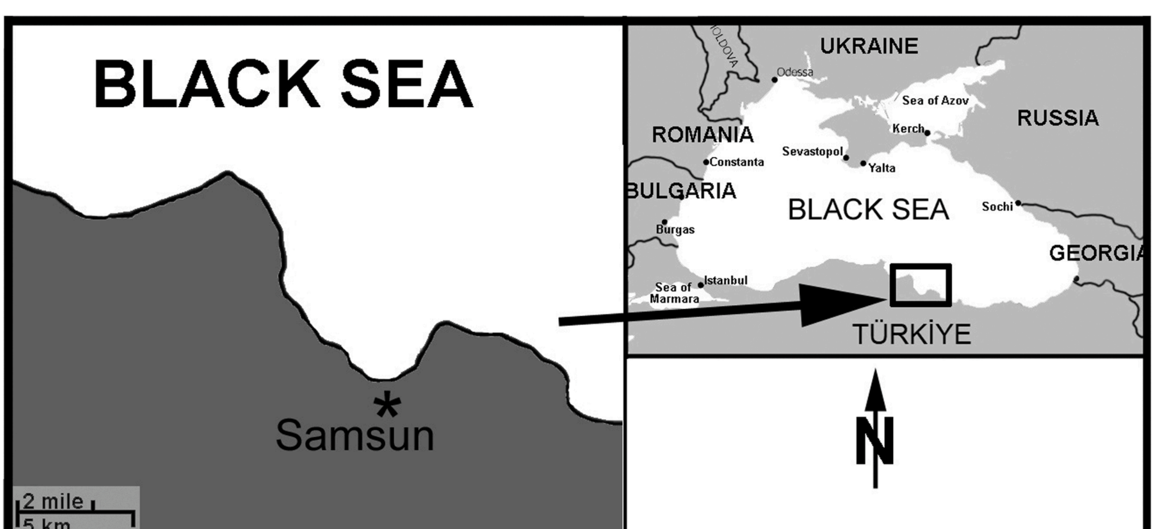

Fig. 1. Samsun coasts of the Black Sea.

2022a, 2022b; Pipoyan et al., 2023).

$$EDI = \frac{C_f \ x \ FIR}{Bwt}$$

where C_f is the concentration of heavy metal in fish samples (mg/kg, wet wt.), FIR is the daily fish ingestion rate (13.7, 27.4 and 41 g/day for infants, children, and adults, respectively) (UNSCEAR, 2010) and B_{wt} is the average body weight (10, 30 and 70 kg for infants, children, and adults, respectively) (UNSCEAR, 2010). EWI values were found by multiplying EDI values by 7.

Non-Carcinogenic hazard (the target hazard quotient (THQ)) and hazardous risk (total hazard quotient (TTHQ))

The noncarcinogenic risk related to the consumption of fish and its associated heavy metals was evaluated using the target hazard quotient (THQ).

$$THQ = \frac{EDI}{Rf.D.}$$

where Rf. D. is the oral reference dose which refers to the estimated maximum permissible health risk associated with daily human consumption of metals in fish. The Rf. D. values for Cd, Hg, Cu, Zn and Fe are 0.0001, 0.0003, 0.04, 0.3 and 0.7 mg/kg/day, respectively (USEPA 2023; RAIS 2023). However, the Rf. D. value for Pb is not given.

The TTHQ estimates the cumulative risk associated with exposure to multiple heavy metals.

$$TTHQ = \sum THQ$$

It is accepted that the likelihood of a health risk is inversely correlated with the combined impacts of metals on the same target organ. TTHQ >1 discloses potential chronic danger while TTHQ <1 implies no potential health risk.

Carcinogenic risk index (CRI)

The CRI is one metric to measure the carcinogenic risk. The equation below represents CRI in terms of:

$$CRI = EDI \ x \ CSF$$

The CSF (cancer slope factor) establishes the risk associated with a lifetime average contaminant dose. CSF value is given for Pb, and this value is 0.0085 per mg/kg-day (USEPA, 2023; RAIS, 2023).

Statistical analysis

The non-parametric tests were implemented during the analysis and to investigate the differences in the concentrations of heavy metals in the sexes the Mann-Whitney U test was conducted. The statistical significance level was accepted as $p<0.05$.

Results and discussion

Heavy metals in S. maximus

Heavy metal concentrations in the edible tissue of turbot are shown in Fig. 2. The increasing order of heavy metals in turbot is as follows: Cd < Hg < Pb < Cu < Fe < Zn. Among the metals analysed in both male and female turbot from the Black Sea coast in 2022, Zn was found in the highest mean concentration. Zn was consistently present at relatively higher levels compared to other metals in both male and female turbot samples. This was followed by Fe.

To compare the concentrations of metals between male and female turbot, we examined the mean values for each metal separately for both genders. Here's a side-by-side comparison of the mean concentrations of Cd, Hg, Pb, Cu, Zn, and Fe in male and female turbot from the Black Sea coast in 2022 (Fig. 2). Except Cd, no significant difference was found between males and females. The mean concentration of Cd is higher in male turbot (0.014 mg/kg) compared to female turbot (0.012 mg/kg). Hg (0.017 mg/kg in males and 0.016 mg/kg in females), Pb (0.022 mg/kg in males and 0.019 mg/kg in females) were slightly higher in males than females. On the other hand, Cu (0.25 mg/kg in males and 0.27 mg/kg in females) and Fe (4.5 mg/kg in males and 5.5 mg/kg in females) concentrations were slightly higher in females than in males. The mean concentration of Zn is similar between male (7.24 mg/kg) and female (7.25 mg/kg) turbot, showing minimal difference. This comparison provides insight into the general metal concentrations in male and female turbot from the Black Sea coast in 2022, indicating potential gender-based variations in metal accumulation in these fish.

Bat et al. (2012) compared the concentrations of Zn, Cu, Pb and Cd in

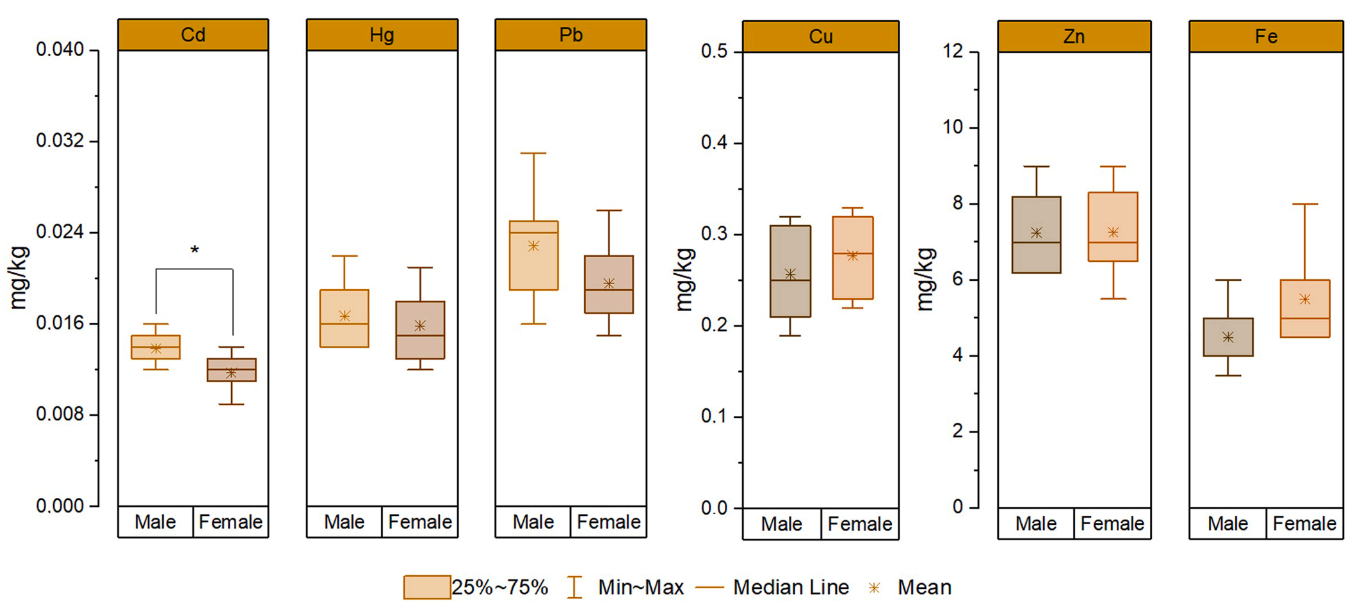

Fig. 2. The means with minimum and maximum levels (vertical line) of heavy metals in the edible tissues of male and female *S. maximus* collected from Samsun coasts of the southern Black Sea. Asterix upper the vertical bars in each graph indicate the values are significantly different ($P<0.05$) between male and female.

Psetta maxima edible muscles from Sinop Coasts of the Black Sea and showed that there was no significant difference between genders except Zn. Similarly, metal levels in male turbot sampled from Sinop coasts (Bat et al., 2012) and Constanta coasts of the Black Sea (Simionov et al., 2019) were found to be higher than female individuals.

Based on the provided Fig. 3 showing monthly measurements of heavy metals in the edible tissues of turbot individuals in 2022. The data reveals variations in the concentrations of heavy metals (Cd, Hg, Pb, Cu, Zn, Fe) in the edible tissues of turbot individuals throughout the year 2022. Both genders exhibited differences in metal accumulation patterns.

Cd levels in both groups showed slight fluctuations from month to month, with the highest values observed in March for males and in September for females. However, Cd concentrations remained within

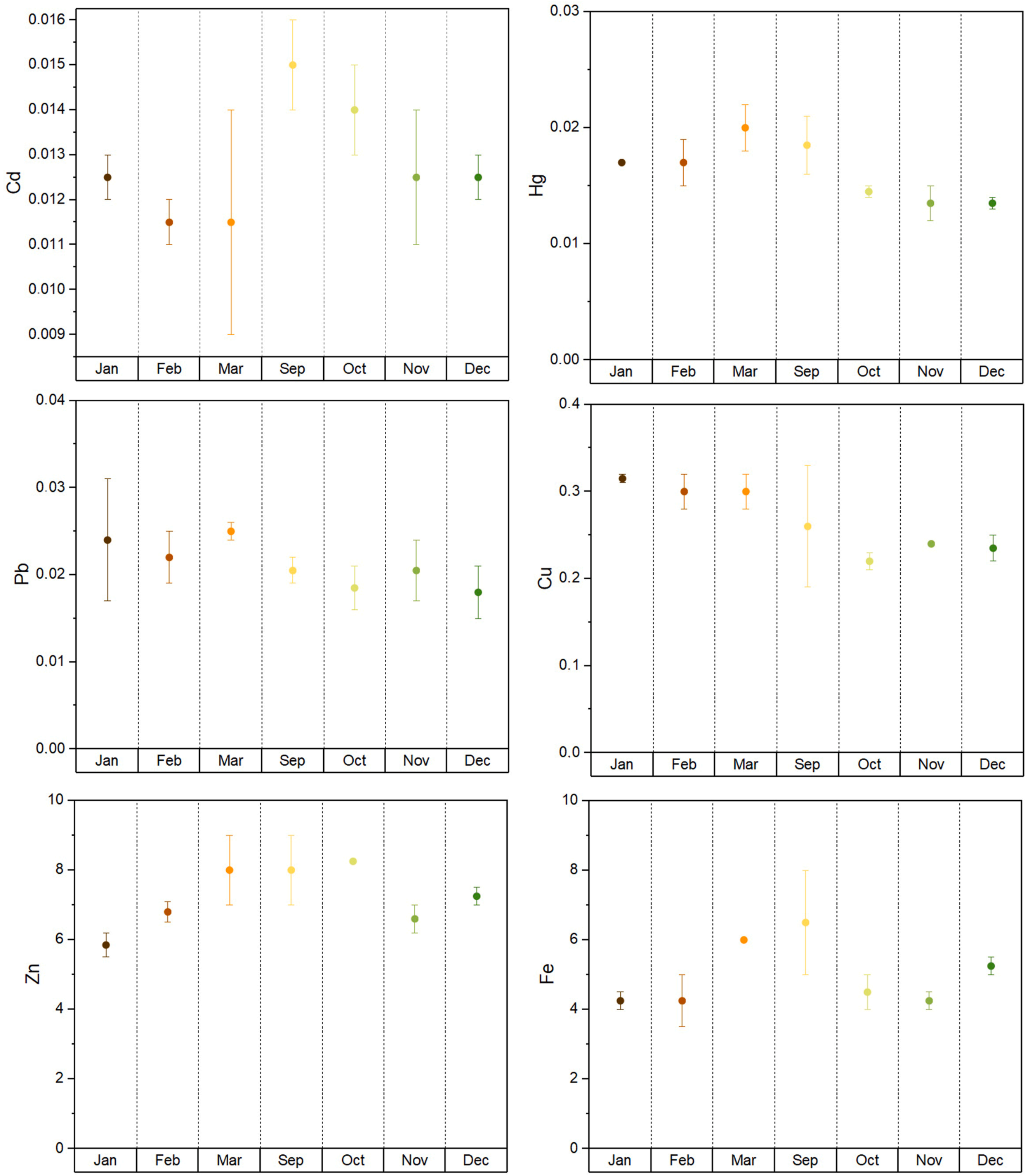

Fig. 3. The mean and minimum and maximum trace elements levels (mg/kg) in the muscle tissues of *S. maximus* in different months.

relatively low ranges in both genders. Both males and females showed fluctuations in Hg concentrations over the months, with peaks in February for males and in March for females. Hg levels remained relatively low and did not exceed alarming levels. Both genders exhibited fluctuations in Pb levels, with a peak in March for males and a peak in March for females. Pb levels remained within acceptable limits for human consumption.

In terms of essential metals, both groups showed variations in Cu levels, with the highest values in March for males and in September for females. Cu levels were generally within safe ranges. Both genders displayed fluctuations in Zn concentrations, with the highest values in March for both groups. Zn concentrations were within safe limits for consumption. Both groups showed fluctuations in Fe levels, with peaks in March for males and in September for females. Fe concentrations were within safe limits for consumption.

The reasons for the differences in the accumulation of metals according to the months are due to the different nutritional level of the fish in different seasons or the change in environmental conditions or both (Ahmed et al., 2014, 2015, 2023; Ahmed and Bat, 2015). Turbot are carnivorous fish that feed on a variety of prey, including other fish, crustaceans, and molluscs (Froese and Pauly, 2023). Some of these prey species may also accumulate heavy metals in their tissues due to their own exposure to contaminated water or sediments. When turbot consume these prey items, they can assimilate the accumulated heavy metals from their diet into their own tissues.

The data of this study suggests that heavy metal concentrations in turbot edible tissues, whether in males or females, generally remained within safe ranges for human consumption throughout the year 2022. However, periodic monitoring is essential to ensure continued safety, especially for toxic element Cd, Hg, and Pb, which showed slight fluctuations and were occasionally higher. Further studies may be required to understand the underlying factors contributing to these variations.

Comparison of metal levels in S. maximus with the results of national, international and previous studies

The results obtained were compared with national and international permissible standards. No data on essential metals are specified in the latest regulations of both the European Commission (2006) and Türkiye (Official Gazette of Republic of Türkiye, 2009) regarding tolerable metal values. In 1995, the permissible limits for Zn and Cu were given in the Official Gazette of the Republic of Türkiye (1995) as 50 and 20 mg/kg wet wt. respectively. No value is given for Fe. On the other hand, permissible limits for toxic metals Cd (Commission Regulation, 2021a), Pb (Commission Regulation, 2021b), and Hg (Commission Regulation, 2022), were given as 0.05, 0.3 and 0.5 mg/kg wet wt. respectively. All metal values measured in the present study are well below the permissible values.

Comparisons of metal accumulations in turbot sampled from different coasts of the Black Sea with previous studies are given in Table 1.

The highest Cd concentration was found fish markets in Kayseri (Duran et al., 2014), followed by Trabzon (Topçuoğlu et al., 1990). These values are notably higher than most other locations, which had Cd levels below 0.1 mg/kg. Cd is a toxic heavy metal that can accumulate in fish tissues and poses health risks to humans if consumed in high quantities.

Hg is highly toxic and can be transformed into methylmercury, a more bioavailable and harmful form. It can also pose significant health risks to humans who consume contaminated fish. In the present study both male and female turbot had relatively low Hg concentrations, suggesting that turbot in this area may have lower Hg contamination. In contrast, the Black Sea had high Hg concentrations in Varna and Burgas based on the data from Manev et al. (2022). This could be due to widespread pollution in the Black Sea.

Pb can enter fish through water, sediment, and prey. Chronic exposure to Pb can affect fish behavior, metabolism, and immune function. The highest Pb concentration was found in Trabzon (Topçuoğlu et al., 1990) followed in Kayseri (Duran et al., 2014), Pb concentrations in most other locations were relatively low (Table 1).

Cu is an essential trace element required for various physiological processes in fish. However, excessive levels can lead to Cu toxicity. Sinop had the highest Cu concentrations (Bat et al., 2006, 2012), followed by Trabzon (Topçuoğlu et al., 1990). Cu is an essential trace element for fish, but high levels can be toxic.

Zn is another essential trace element for fish, involved in enzyme function and metabolism. It can interfere with ion balance, causing osmoregulatory disturbances and altering enzymatic activities. Tuzen (2009) found the highest Zn concentration in the Black Sea, followed by Trabzon (Topçuoğlu et al., 1990) and Sinop coasts (Bat et al., 2006, 2012).

Fe is an essential element for fish, playing a crucial role in oxygen

Table 1
Comparison of metals in turbot with values got from the literature as mg/kg wet wt. (*dry wt.).

Area	Cd	Hg	Pb	Cu	Zn	Fe	References
Trabzon	0.30±1.7		2.38±0.09	4.2 ± 0.6	38.6 ± 4.1	31.0 ± 1.7	Topçuoğlu et al., 1990
Sinop	0.053		0.525	5.05	32.93	39.84	Bat et al., 2006
Sinop*	0.272		2.72	26.14	170.5	113.3	Bat et al., 2006
Black Sea	0.10±0.01	0.045±2	0.28±0.02	0.75±0.05	45.2 ± 2.7	36.2 ± 2.4	Tuzen, 2009
Sinop*	<0.02	0.065±0.001	<0.05				Das et al., 2009
Samsun, Sinop, Terme, Fatsa, Ordu*	0.022±0.007		0.73±0.21	2.13±0.21	24.83±1.71	21.72±0.83	Nisbet et al., 2010
Sinop	0.04±0.01		0.17±0.04	5.18±0.69	32.2 ± 2.51		Bat et al., 2012
Sinop	0.02±0.001		0.09±0.02	2.84±0.85	22.01±4.03		Bat et al., 2012
Kayseri	0.54±0.09		0.82±0.11	0.8 ± 0.09		92.3 ± 2.93	Duran et al., 2014
Sinop	0.021±0.005		0.42±0.10	0.75±0.25		48.60±9.06	Ergönül and Altindağ, 2014
Bulgarian	0.005±0.001	0.08±0.010	0.01±0.01	0.19±0.01	4.8 ± 0.4		Peycheva et al., 2016
Sinop				0.54			Bat et al., 2017
Southwest Black Sea	0.01±0.01	0.01±0.01	0.17±0.29	4.29±5.85	17.57±14.46		Mol et al., 2017
Black Sea*	0.027	0.065	0.191				Kuplulu et al., 2018
Romania	0.03±0.001			0.15±0.01	10.3 ± 2.9	12.25±2.39	Simionov et al., 2019
Romania	0.03±0.001			0.15±0.01	14.06±1.43	6.01±1.25	Simionov et al., 2019
Sinop	0.011±0.004	0.017±0.003	0.07±0.005	1.32±0.28	14±3		Bat et al., 2019
Eastern Black Sea*	0.01		0.02	0.62	22.7		Alkan et al., 2020
Eastern Black Sea*	0.05		0.01	0.37	13.65		Alkan et al., 2020
Varna	<0.05	0.15±0.02	<0.05		6.58±0.66		Manev et al., 2022
Burgas	<0.05	0.20±0.04	<0.05		1.82±0.36		Manev et al., 2022
Sinop	0.01±0.006	0.03±0.01	0.09±0.04				Bat et al., 2022a
Samsun (male turbot)	0.014±0.001	0.017±0.002	0.022±0.004	0.25±0.04	7.24±1.02	4.5 ± 0.86	This study
Samsun (female turbot)	0.012±0.001	0.016±0.003	0.019±0.003	0.27±0.04	7.25±1.15	5.5 ± 1.22	This study

transport and enzyme function. However, excessive Fe levels can cause oxidative stress and lead to iron toxicity. Fe concentrations were relatively consistent across most locations, with Kayseri (Duran et al., 2014) and Sinop (Ergönül and Altindağ, 2014) having the highest Fe levels.

In summary, the data suggests that there is considerable variation in metal concentrations in turbot depending on the location. Some areas, exhibit higher levels of certain metals (Table 1), which could be due to local environmental factors, industrial activities, or pollution sources. Based on the provided data of heavy metal concentrations in turbot from the Black Sea coast in 2022, we can scientifically state that the amount of metals in this fish species is relatively low and below the established standards set by regulatory authorities for human consumption.

Health risk analysis evaluation

It's important to note that the process of metal accumulation in fish tissues can vary based on the specific metal, environmental conditions, and the fish's physiological state. Accumulation of heavy metals in fish tissues is a concern from both ecological and public health perspectives, as it can lead to biomagnification in the food chain and potential health risks for both marine organisms especially benthic biota like turbot and humans who consume fish as part of their diet. Therefore, monitoring and understanding the factors influencing metal accumulation in fish species like turbot are crucial for ensuring food safety and the overall health of marine ecosystems.

The mean concentrations of Cd, Hg, Pb, Cu, Zn, and Fe in both male and female turbot samples were found to be within acceptable levels according to national and international allowable concentrations for heavy metals in fish intended for human consumption. These allowable limits are typically set by food safety authorities based on comprehensive risk assessments to ensure public health protection.

Table 2 shows the estimated daily intakes (EDIs), the estimated weekly intakes (EWIs), the target hazard quotient (THQ), total hazard quotient (TTHQ) and cancer risk index (RI) of heavy metals for different age groups (infants, children, adults) consuming male and female turbot from the Black Sea coast.

The EDI values of Cd for both male and female turbot consumers (infants, children, adults) are very low, ranging from 6.86×10^{-6} to 1.80×10^{-5} mg/kg/day. These values are well below the respective Rf. D. (0.0001), indicating that the amount of Cd consumed through turbot is within safe levels. The EDI values of Hg for both male and female turbot consumers range from 9.29×10^{-6} to 2.17×10^{-5} mg/kg/day. These values are also below the Rf. D. (0.0003), suggesting that the consumption of turbot does not pose significant health risks associated with Hg exposure. The EDI values of Cu for both male and female turbot consumers range from 1.51×10^{-4} to 3.60×10^{-4} mg/kg/day. These values are considerably lower than the Rf. D. (0.04), suggesting that the amount of Cu consumed through turbot is safe for human health. The EDI values of Zn for both male and female turbot consumers range from 4.24×10^{-3} to 9.43×10^{-3} mg/kg/day. These values are well below the Rf. D. (0.3), indicating that the consumption of turbot does not pose any significant health risks related to Zn intake. The EDI values of Fe for both male and female turbot consumers range from 2.64×10^{-3} to 7.15×10^{-3} mg/kg/day. These values are below the Rf. D. (0.7), indicating that the amount of Fe consumed through turbot is safe (USEPA, 2023).

The EDI values of Pb for both male and female turbot consumers range from 1.15×10^{-5} to 2.97×10^{-5} mg/kg/day. Like other metals, these values are below the CSF (0.0085), indicating that the consumption of turbot does not lead to harmful Pb exposure (USEPA, 2023; RAIS, 2023).

The THQ values for Cd, Hg, Cu, Zn, and Fe are below 1 for both male and female turbot, indicating that the noncarcinogenic health risk associated with these metals intake through turbot consumption is negligible. Similarly, the RI values for Pb are exceptionally low for both male and female turbot, implying a minimal carcinogenic risk associated with Pb intake through turbot consumption.

Based on these scientific findings and assessments (see Table 2), we can confidently state that the concentration of heavy metals in turbot from the Black Sea in 2022 is within safe and acceptable limits for human consumption. The fish can be considered safe for consumption, and the levels of heavy metals in their tissues do not pose significant health risks to consumers, including infants, children, and adults.

Table 2
The EDIs and EWIs for all heavy metals, THQs and TTHQ for Cd, Hg, Cu, Zn and Fe, and cancer risk index (RI) for Pb in age groups consuming *S. maximus*.

Metal	Sex	EDI			EWI			THQ			CRI		
		(infants)	(children)	(adults)	(infants)	(children)	(adults)	(infants)	(children)	(adults)	(infants)	(children)	(adults)
Cd	male	1.80×10^{-5}	1.25×10^{-5}	8.12×10^{-6}	1.26×10^{-4}	8.73×10^{-5}	5.68×10^{-5}	1.80×10^{-2}	1.25×10^{-2}	8.12×10^{-3}			
	female	1.52×10^{-5}	1.05×10^{-5}	6.86×10^{-6}	1.07×10^{-4}	7.38×10^{-5}	4.80×10^{-5}	1.52×10^{-2}	1.05×10^{-2}	6.86×10^{-3}			
Hg	male	2.17×10^{-5}	1.50×10^{-5}	9.79×10^{-6}	1.52×10^{-4}	1.05×10^{-4}	6.85×10^{-5}	7.24×10^{-2}	5.01×10^{-2}	3.26×10^{-2}			
	female	2.06×10^{-5}	1.43×10^{-5}	9.29×10^{-6}	1.44×10^{-4}	9.99×10^{-5}	6.50×10^{-5}	6.87×10^{-2}	4.76×10^{-2}	3.10×10^{-2}			
Pb	male	2.97×10^{-5}	2.06×10^{-5}	1.34×10^{-5}	2.08×10^{-4}	1.44×10^{-4}	9.37×10^{-5}				2.53×10^{-7}	1.75×10^{-7}	1.14×10^{-7}
	female	2.54×10^{-5}	1.76×10^{-5}	1.15×10^{-5}	1.78×10^{-4}	1.23×10^{-4}	8.02×10^{-5}				2.16×10^{-7}	1.50×10^{-7}	9.74×10^{-8}
Cu	male	3.34×10^{-4}	2.31×10^{-4}	1.51×10^{-4}	2.34×10^{-3}	1.62×10^{-3}	1.05×10^{-3}	8.36×10^{-3}	5.79×10^{-3}	3.77×10^{-3}			
	female	3.60×10^{-4}	2.49×10^{-4}	1.62×10^{-4}	2.52×10^{-3}	1.75×10^{-3}	1.14×10^{-3}	9.01×10^{-3}	6.24×10^{-3}	4.06×10^{-3}			
Zn	male	9.42×10^{-3}	6.52×10^{-3}	4.24×10^{-3}	6.59×10^{-2}	4.56×10^{-2}	2.97×10^{-2}	3.14×10^{-2}	2.17×10^{-2}	1.41×10^{-2}			
	female	9.43×10^{-3}	6.53×10^{-3}	4.25×10^{-3}	6.60×10^{-2}	4.57×10^{-2}	2.98×10^{-2}	3.14×10^{-2}	2.18×10^{-2}	1.42×10^{-2}			
Fe	male	5.85×10^{-3}	4.05×10^{-3}	2.64×10^{-3}	4.10×10^{-2}	2.84×10^{-2}	1.85×10^{-2}	8.36×10^{-3}	5.79×10^{-3}	3.77×10^{-3}			
	female	7.15×10^{-3}	4.95×10^{-3}	3.22×10^{-3}	5.01×10^{-2}	3.47×10^{-2}	2.26×10^{-2}	1.02×10^{-2}	7.07×10^{-3}	4.60×10^{-3}			
	male						**TTHQ**	$\mathbf{1.39 \times 10^{-1}}$	$\mathbf{9.59 \times 10^{-2}}$	$\mathbf{6.24 \times 10^{-2}}$	**Total CRI**	$\mathbf{5.41 \times 10^{-7}}$	
	female							$\mathbf{1.35 \times 10^{-1}}$	$\mathbf{9.32 \times 10^{-2}}$	$\mathbf{6.06 \times 10^{-2}}$		$\mathbf{4.63 \times 10^{-7}}$	

Conclusion

The turbot is a highly sought-after fish species in the Black Sea, and its commercial importance (Tserkova et al., 2023) makes it a significant contributor to the regional economy (Aydın, 2011). Its culinary excellence contributes to the region's gastronomic reputation and attracts tourists and food lovers, boosting the local hospitality and tourism industries. Being expensive and in high demand, the turbot fishery provides livelihoods and income opportunities for local fishermen, supporting the coastal communities' economic well-being (Bat et al., 2013, 2018b).

These findings of the present study highlight that turbot from the Black Sea coast is safe for human consumption, with the accumulation of heavy metals being within acceptable limits. Regular monitoring of heavy metal concentrations in fish and their environment remains essential to ensure long-term food safety and maintain the ecological balance of the Black Sea ecosystem.

The accumulation of heavy metals in turbot tissues highlights the importance of monitoring and understanding the levels of these metals in the Black Sea ecosystem. It is crucial for managing fishery resources sustainably, ensuring food safety for human consumers, and preserving the overall health of the marine environment. Additionally, research on the interactions and effects of multiple metals on turbot can further improve our understanding of the ecological impacts of heavy metal pollution in the Black Sea.

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Author contributions

Levent Bat: Conceptualization, literature review, methodology, health risk assessment, investigation, writing – review and editing; Öztekin Yardım: Fish procurement, preservation, preparation for analysis; Ayşah Öztekin: Drawing graphs, statistical calculations; Elif Arıcı: Literature review, preparation of comparative table. All authors contributed to the study conception and design. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data supporting the findings of this study are available within the manuscript.

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