Environmental Management (2021) 67:522–531
https://doi.org/10.1007/s00267-020-01352-y

Heavy Metal Concentrations in *Trachurus Mediterraneus* and *Merlangius Merlangus* Captured from Marmara Sea, Turkey and Associated Health Risks

Latife Köker[1] · Fatih Aydın[1] · Özcan Gaygusuz[1] · Reyhan Akçaalan[1] · Derya Çamur[2] · Hüseyin İlter[3] · Ferruh Niyazi Ayoğlu[4] · Ahmet Altın[5] · Murat Topbaş[6] · Meriç Albay[1]

Received: 20 April 2020 / Accepted: 21 August 2020 / Published online: 6 September 2020
© Springer Science+Business Media, LLC, part of Springer Nature 2020

Abstract

Rapid industrialization and excessive human population growth may cause deterioration in marine water quality and biodiversity. Heavy metals are one of the most common pollutants in the seas and marine organisms, including demersal and pelagic fish, can accumulate them from the environment. Assessment of the ecological risk of heavy metals from fish has an important role in public health. In this study, some heavy metal (Pb, Cd, As, Cr, Hg, Cu, Zn, and Fe) concentrations were determined in the muscle tissues of two commonly consumed fish species, *Trachurus mediterraneus* (Mediterranean horse mackerel) and *Merlangius merlangus* (Whiting), which are the fifth (14,222 tons/year) and sixth (6814 tons/year) highest commercial catches of marine fish species in Turkey, respectively. Heavy metal concentrations of samples collected from four sites (Adalar, İzmit Bay, Yalova, and Tekirdağ) in the Marmara Sea were determined using ICP-MS. Fish samples caught at Yalova station were found to have the highest heavy metal concentrations. According to the World Health Organization (WHO), in terms of the mean values, only As, and Cr were higher than permissible limits in *T. mediterraneus*, while Pb, Cd, As, and Cr were higher in *M. merlangus*. Arsenic concentrations were higher than maximum limits in both *T. mediterraneus* and *M. merlangus*. The estimated weekly intake (EWI) was calculated to assess the potential health impact. The EWI for arsenic, cadmium, lead, and mercury for some sites was above the provisional tolerable weekly intake.

Keywords Bioaccumulation · Heavy metals · Tissue concentration · Health risk · *Trachurus mediterraneus* · *Merlangius merlangus*

Introduction

Heavy metals are found in marine ecosystems as a consequence of daily anthropogenic activities. Even though they can naturally be found in aquatic ecosystems, particularly, over the last few decades, agriculture and industry have contributed further to the release of wastes including heavy metals into the environment (Gümgüm et al. 1994; Miri et al. 2017; Carolin et al. 2017). Heavy metal pollution has become a worldwide problem because of toxic effects and bioaccumulation in aquatic organisms (Censi et al. 2006; Zeitoun and Mehana 2014; Lee et al. 2019). Among aquatic organisms, fish are the most frequently exposed organisms to the harmful effects of these pollutants (Clarkson 1998; Olaifa et al. 2004). Due to its accumulation in fish, heavy metals can be transmitted to humans through the food chain and cause negative effects on human health and the ecosystem in the long term (Gao and Li 2012;

✉ Latife Köker
latife.koker@istanbul.edu.tr

1 Department of Marine and Freshwater Resources Management, Faculty of Aquatic Sciences, Istanbul University, Istanbul 34130, Turkey

2 Department of Public Health, Faculty of Gülhane Medicine, University of Health Sciences, Ankara, Turkey

3 Provincial Health Directorate, Ministry of Health, Ankara, Turkey

4 Department of Public Health, Faculty of Medicine, Bülent Ecevit University, Zonguldak, Turkey

5 Department of Environmental Engineering, Bülent Ecevit University, Zonguldak 67100, Turkey

6 Department of Public Health, Faculty of Medicine, Karadeniz Technical University, Trabzon, Turkey

Hu et al. 2013; Zhao et al. 2014). Heavy metals like Cu, Zn, and Fe are essential for fish metabolism while some others such as Hg or Pb have no known role in biological systems. While essential metals (Fe, Zn, Cu, Mg, Se, Co, and Vn) have taken up by fish, non-essential ones (Al, As, Cd, Sb, Sn, Pt, Hg, Pb, and Bi) are also taken and accumulate in their tissues (Munoz-Olivas and Camara 2001; Predescu et al. 2017). Furthermore, their concentrations varied greatly in different parts of the fish (Canlı and Atlı 2003; Alkan et al. 2016). Besides the type of heavy metal, there are many environmental, ecological, and physiological parameters which affect the bioaccumulation of heavy metals in fish such as temperature, pollutant type, feeding habitats, age/life span (Wagner and Boman 2003; Weber et al. 2013; Rejomon et al. 2010; Mziray and Kimirei 2016; Burada et al. 2017). Also, the sizes of fish play an important role in metal contents of tissue (Barak and Mason 1990; Monterio and Lopes 1990).

Turkey is surrounded by four different seas and fishing is one of the biggest income sources for the country. The Marmara Sea, which is a semi-enclosed inland sea, has an area of 11,350 km^2. The rapid population growth, distorted urbanization, and the density of industry are the main factors for pollution in the Marmara Sea and different types of pollutants often reach the sea through river discharges (Pekey et al. 2004). The northeast coastline area of the Marmara Sea is the most industrialized region of Turkey, in which Izmit Bay has been especially affected by industrialization (Okay et al. 1998; Coelhan et al. 2006; Ergül et al. 2018). It is also heavily urbanized with 1/3 of Turkey's population living around the sea of Marmara. Heavy metals have also been discharged into the Marmara Sea for many years. Despite all these factors, the fisheries in the Marmara Sea are based on coastal fishing of benthic/demersal species and fishing of pelagic fish that rests upon seasonal migration fact. Pelagic fish, such as anchovy, bluefish, horse mackerel, and demersal fish, hake, whiting, striped red are the most consumed marine foods in Turkey (TUIK 2018). In 2018, *Trachurus mediterraneus* (Steindachner 1868) and *Merlangius merlangus* (Linnaeus 1758) were the fifth (14,222 tons/year) and sixth (6814 tons/year) most landed fish species in Turkey, respectively (TUIK 2018). In addition, these two species are also the most commercially caught fish species in the Marmara Sea (5000 tons/year and 1000 tons/year, respectively; TUIK 2018). Many studies have been focused on the determination of heavy metals in anchovy, horse mackerel, sea bass, and whiting which are commonly consumed in Turkey (Keskin et al. 2007; Türkmen et al. 2008a, b; Berik and Kahraman 2012; Özden and Erkan 2016; Güngör and Kara 2018). In some of these studies showed that the heavy metal concentrations of some fish species were below permissible limits while the others were over limits that indicating metal pollution in the Marmara Sea (Keskin et al. 2007; Türkmen et al. 2008a; Özden and Erkan 2016). Türkmen et al. (2008c) reported that lead levels in muscles of anchovy in Yalova were just higher than the Turkish permissible limit. Cucu et al. (2019) found, during the sampling period (2013), that cadmium and lead were lower than Turkish limits for *T. mediterraneus* and *M. merlangus* on the Gebze Region in the Marmara Sea. In these previous studies in the Marmara Sea, fish samples were either obtained from local fish markets (Demirkol and Aktaş 2002; Topcuoğlu et al. 2003; Türksönmez and Diler 2019) or sampling was done only from one region (Kayhan et al. 2017; Güngör and Kara 2018; Cucu et al. 2019).

The main objective of the present study was to investigate the concentration of heavy metals (arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), mercury (Hg) and zinc (Zn)) in the fish tissues of pelagic *T. mediterraneus* (Mediterranean horse mackerel) and demersal *M. merlangus* (Whiting), which are economically important fish species caught in the Marmara Sea. It is aimed to reveal the effects of heavy metal pollution in two fish species on public health by sampling from four stations that represent the Marmara Sea. Health risks posed by the heavy metals to humans consuming these fish were also evaluated.

Materials and Methods

Fish were sampled seasonally, four times from February to October in 2018, by bottom trawling at four different sites in the coastal waters of the Marmara Sea in 2018 (Fig. 1). Sampling areas were selected in metropolitan areas where the intensive commercial fishery is operating in the Sea of Marmara which were Adalar (1. St), the entrance of İzmit Bay (2. St), Yalova (3. St), and Tekirdağ (4. St).

Fish samples were stored in cold conditions (−18 °C) immediately after being caught, then transferred to the Limnology laboratory for further analyses. Total length (TL) was measured to the nearest 0.1 cm and body weight (*W*) was weighed to the nearest 0.1 g. Dissected muscle samples were homogenized and ~1.0 g muscle tissue sample from each fish specimen was taken and washed with distilled

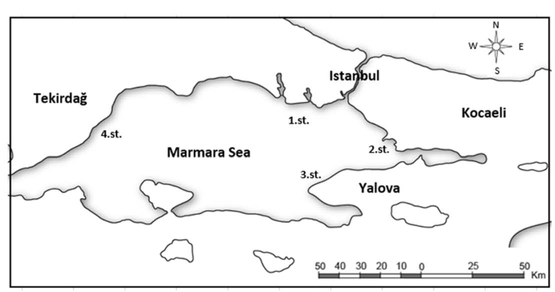

Fig. 1 Fish sampling sites in the Marmara Sea, Turkey

water. Samples were digested with nitric acid and hydrogen peroxide (2:1) in a microwave digestion system (MWS 4, Berghof) (Guhathakurta and Kaviraj 2000) and were transferred to 50 ml flasks. After the samples were filtered through a 0.45 µm nitrocellulose membrane filter, they were introduced into the ICP-MS (Perkin Elmer ELAN-DRC-e). All reagents used were of analytical grade (Merck). All the analyses were performed in triplicate by ICP-MS (Perkin Elmer ELAN-DRC-e). The operational parameter settings used for the ELAN 6000 Perkin Elmer were shown in Table 1 (Chamberlain et al. 2000). Multi-element (Merck) standards were used for standard solutions prepared from stock solutions. For mercury analyses, a trace amount of gold solution added to HNO_3 preserved all forms of mercury.

The accuracy of the analysis was verified by analyzing the ERM-BB422 certified reference material (Fish Muscle European Reference Material). Instrumental limits of detection (LOD), the instrumental limit of quantification (LOQ), and relative standard deviation (RSD) were calculated (Mataveli et al. 2013). The calculation of the detection limit is based on the 3x of SD of the blank solution. Recoveries between 98 and 105% were accepted to validate the calibration. %RSD values were varied between 0.63 and 8.15%. Values were expressed as the mean of three analyses for each sample. LOD and LOQ of elements were Pb 0.001–0.003 µg L^{-1}; Cd 0.002–0.007 µg L^{-1}; As 0.004–0.013 µg L^{-1}; Cr 0.009–0.030 µg L^{-1}; Zn 0.010–0.033 µg L^{-1}; Cu 0.006–0.012 µg L^{-1}; Hg 0.005–0.017 µg L^{-1} and Fe 0.012–0.040 µg L^{-1}, respectively.

Prior to statistical analyses, data sets were tested for normality and homogeneity. Because the data showed not normal distribution considering the Shapiro–Wilk test, non-parametric tests (Mann–Whitney *U* and Kruskal–Wallis) were selected. Non-parametric Mann–Whitney *U* test was performed to determine the differences, and the Kruskal–Wallis test (KW) (with Tamhane's as a post-hoc test) was performed to determine differences of body size groups (small, medium, large) for each fish species, in terms of heavy metal concentrations (As, Cd, Cr, Cu, Fe, Hg, Pb, and Zn). The level of significance was set at $p < 0.05$.

The estimated weekly intake (EWI) values of heavy metals were calculated. Since, the annual quantity of fish consumed was 5.5 kg/person in 2017 (TUIK 2017), the EWI and EDI (Estimated Daily Intake) values were assumed as being for a 70 kg person who would consume 105.5 g fish/week. Furthermore, Provisional Tolerable Weekly Intake (PTWI) was calculated to represent the maximum amount of pollutant that a person could be exposed to per week throughout a lifetime without risk of an unacceptable health impact (National Academy of Sciences 1989; WHO 1996; Council of Europe 2001; FAO/WHO 2010; EFSA (2010, 2012a, b)).

Table 1 Instrumental parameters of ICP-MS

Characteristics	Instrumen conditions
RF Power	1400 W
Nebulizer gas	Argon
Plasma gas flow	14.0 L/min
Auxiliary gas flow	1.4 L/min
Nebulizer gas flow	0.99 L/min
Sweeps/reading	10
Number of replicates	3
Sampler & skimmer cone	Nickel

Results and Discussion

A total of 201 fish specimens ($n = 111$ for *T. mediterraneus*; $n = 90$ for *M. merlangus*) were sampled during the

Table 2 Individual numbers (*n*), body weight and total length distributions of *T. mediterraneus* and *M. merlangus* in each sampling site in the Marmara Sea

	Number	Body weight (W, g)		Total length (TL, cm)	
	n	Min.–max.	Mean	Min.–max.	Mean
1.st					
T. mediterraneus	15	5.3–23.3	12.9 ± 5.2	9.4–14.8	11.9 ± 1.6
M. merlangus	30	11.2–55.1	22.8 ± 9.9	11.4–18.9	14.4 ± 1.8
2.st					
T. mediterraneus	19	5.4–28.4	15.75 ± 4.4	9.6–15.2	12.5 ± 1.1
M. merlangus	14	10.8–29.6	13.8 ± 1.8	11.1–16.3	13.1 ± 0.9
3.st					
T. mediterraneus	29	4.0–16.0	11.7 ± 1.7	9.0–13.1	11.5 ± 0.6
M. merlangus	16	11.0–14.1	12.5 ± 4.6	11.9–3.5	12.9 ± 1.4
4.st					
T. mediterraneus	48	4.4–24.2	9.8 ± 4.5	8.6–14.1	10.7 ± 1.4
M. merlangus	30	7.9–31.6	14.9 ± 6.3	10.7–16.4	12.8 ± 1.5

Table 3 Mean heavy metal concentrations (mg kg^{-1}) in each length class of *T. mediterraneus* and *M. merlangus* caught from the Mediterranean Sea

	Total length (cm)	Heavy metal concentrations (mg kg^{-1})							
		Cr	Fe	Cu	Zn	As	Cd	Pb	Hg
T. mediterraneus									
Small	8.5–10.9 cm	0.22	23.0	1.26	23.35	16.09	0.24	0.40	0.03
Medium	11–12.9 cm	0.15	20.63	1.89	17.40	17.53	0.26	0.30	0.13
Large	13–15.5 cm	0.11	15.72	0.93	15.34	13.22	0.13	0.04	0.08
M. merlangus									
Small	10–12.9 cm	0.41	23.22	0.41	16.16	23.47	0.93	0.28	0.02
Medium	13–15.9 cm	0.34	17.99	0.31	12.10	24.33	1.38	0.39	0.01
Large	16–19 cm	0.31	14.68	0.30	10.60	21.28	0.84	0.21	0.15

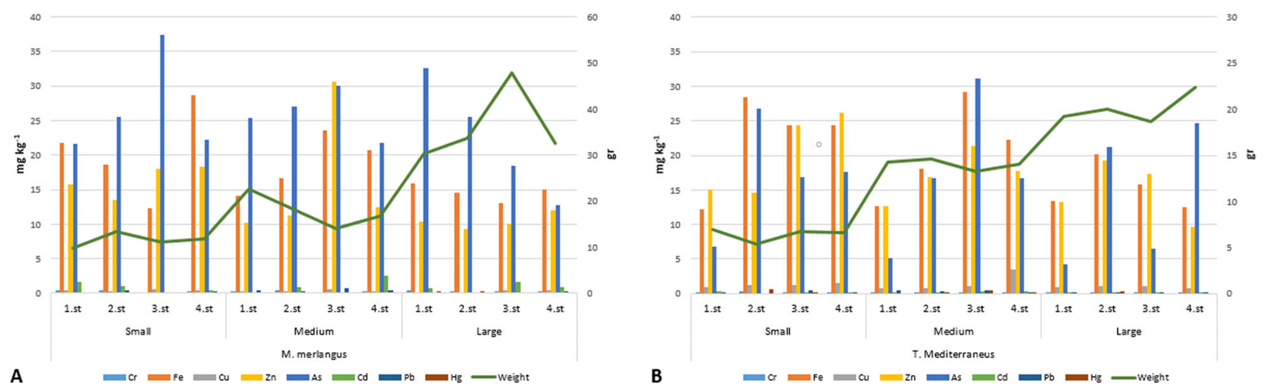

Fig. 2 Mean values of heavy metals in different size of **a** *T. mediterraneus* and **b** *M. merlangus*

study period and all of them were analysed for heavy metal concentrations. The TL and body-weight of the specimens varied between 8.6–15.2 cm and 4.0–28.4 g for *T. mediterraneus* and 10.2–18.9 cm and 6.4–55.1 g for *M. merlangus* (Table 2).

While evaluating the relationship between length and heavy metals, both species were classified and grouped according to their size. *T. mediterraneus* and *M. merlangus* were grouped as small (8.5–10.9 cm; 10–12.9 cm), medium (11–12.9 cm; 13–15.9 cm) and large (13–15.5 cm; 16–19 cm), respectively (Table 3). Heath (1995) reported that because of the large surface to the volume ratio, small fish tend to accumulate a higher quantity of heavy metals. Our results also showed that generally, the smaller sized specimens of both species had higher heavy metal concentrations. For *T. mediterraneus*, the Kruskal–Wallis test revealed significant differences between small and large size group and was found for Cr ($p = 0.000$), Fe ($p = 0.001$), Cu ($p = 0.002$), Zn ($p = 0.008$), Cd ($p = 0.002$) and Pb ($p = 0.042$). For *M. merlangus*, Cr ($p = 0.000$), Fe ($p = 0.000$) and Cu ($p = 0.044$) showed significant differences (Kruskal–Wallis, $p < 0.05$). Metal metabolism and metabolic activity in fish played a key role in metal accumulation (Heath 1995; Roesijadi and Robinson 1994). The studies examining the relationship between length and heavy metals showed that the accumulation of heavy metals decreased with an increase in the length of fish (Liang et al. 1999; Nussey et al. 2000; Widianarko et al. 2000; Canlı and Atlı 2003). The reason for negative correlations between length and metal concentrations could be explained by the fact that young individuals had higher metabolic activity than older ones (Elder and Collins 1991; Canlı and Furness 1993) (Fig. 2). There is a general view that Zn and Cu concentrations, in particular, decrease with increasing body size due to different metabolic rates of accumulation (Canlı and Atlı 2003; Endo et al. 2008; Barone et al. 2013) and this view was supported by the results of the present study.

The results of the concentration of seven elements (Pb, Cd, As, Cr, Hg, Zn, Cu, and Fe) in the muscle of two species from the Marmara Sea are shown in Table 4. The concentration of As, Zn, and Fe were the highest in both species. On the other hand, generally the lowest concentrations for Cd, Pb, and Cr were found during the study period (Table 4).

The order of mean heavy metals concentrations from all stations was found to be Fe > Zn > As > Cu > Pb > Hg > Cd > Cr for *T. mediterraneus*. Although this pattern depending on the environment of the fish, this general order of monitored heavy metal bioaccumulation in pelagic fish is similar to that found in other studies (Bilandzic et al. 2011; Afandi et al. 2018). The concentrations of all heavy metals determined in *M. merlangus* were low from all stations, except

Table 4 Mean heavy metal contents with standard error in the tissues of the examined species (mg kg^{-1} wet wt)

	T. mediterraneus				*M. merlangus*			
Heavy metals	1.st	2.st	3.st	4.st	1st	2.st	3.st	4.st
Cd	0.2 ± 0.06	0.2 ± 0.03	0.3 ± 0.01	0.2 ± 0.05	0.5 ± 0.05	ND	0.2 ± 0.06	1.4 ± 0.25
Pb	0.3 ± 0.03	0.3 ± 0.01	0.8 ± 0.04	0.2 ± 0.03	0.3 ± 0.06	1.2 ± 0.03	0.9 ± 0.13	0.3 ± 0.08
As	5.4 ± 0.55	14.2 ± 1.15	28.1 ± 8.01	15.1 ± 2.83	24.2 ± 1.33	14.4 ± 2.15	35.5 ± 6.95	21.2 ± 4.03
Cr	0.2 ± 0.03	0.2 ± 0.02	0.2 ± 0.02	0.2 ± 0.03	0.3 ± 0.02	0.2 ± 0.02	0.3 ± 0.01	0.4 ± 0.08
Cu	0.9 ± 0.21	0.9 ± 0.25	1.0 ± 0.17	2.0 ± 0.38	0.3 ± 0.02	0.4 ± 0.15	0.6 ± 0.04	0.4 ± 0.01
Zn	14.1 ± 2.41	15.7 ± 1.71	21.0 ± 3.14	20.0 ± 5.31	10.6 ± 1.73	11.8 ± 2.33	19.6 ± 2.33	17.2 ± 2.31
Fe	12.9 ± 1.38	58.1 ± 11.9	83.0 ± 10.75	19.8 ± 4.64	15.9 ± 2.29	51.5 ± 9.43	63.1 ± 12.57	25.0 ± 3.64
Hg	ND	0.3 ± 0.02	0.4 ± 0.15	0.1 ± 0.01	0.1 ± 0.02	0.03 ± 0.01	0.4 ± 0.02	0.1 ± 0.01

ND not detected

As, Zn, and Fe. The order of mean heavy metals concentrations from all stations was found to be Fe > As > Zn > Cd > Pb > Cu > Cr > Hg for *M. merlangus*.

According to comparisons between two species for heavy metal concentrations, performed by the non-parametric Mann–Whitney test, there were significant differences in levels of all heavy metals Cr, Cu, Zn, Cd, Pb, and As (Mann–Whitney, $p < 0.05$), except for iron and mercury ($p > 0.05$). The cadmium, iron, arsenic, chromium, and lead concentrations were greater in *M. merlangus* than *T. mediterraneus*. However, copper, zinc, and mercury were higher in *T. mediterraneus*. Similar to other studies in the Marmara Sea, Fe was the highest in both species in this study, followed by As. On the other hand, Cd was generally the lowest (Türkmen et al. 2008a, 2009). Especially at Yalova, for both species, As, Zn, Fe, and Hg showed the highest values and Pb displayed the highest value in *M. merlangus* at Site 2, the entrance to İzmit Bay.

The concentrations of Cr, Cu, As, Pb, Cd, Hg, Zn, and Fe in *T. mediterraneus* and *M. merlangus* from different sites of the Marmara Sea were compared with national and international standards. Values concerning permissible detected heavy metals for Turkish Fisheries Laws and Regulations (TKB), World Health Organization (WHO) and Environmental Protection Agency (EPA) are given in Table 5 (WHO 1989; EPA 1989; Anonymous 2005). *Trachurus mediterraneus* and *M. merlangus* results were averaged for all stations.

Demersal fishes can have a higher heavy metal accumulation potential, because they are exposed to more heavy metals due to their habitats, feeding habits and placing in high trophic levels (Stergiou and Karpouzi 2002; Naccari et al. 2015). According to permissible limits of national and international standards, our data show that pelagic fish had lower Pb ($p = 0.000$), Cd ($p = 0.008$), As ($p = 0.000$), and Cr ($p = 0.000$) concentrations than demersal fish (Mann–Whitney, $p < 0.05$), (Table 5). TKB has very low permissible limits and both fish exceeded the limits for Cd, As, and Pb. According to the WHO, only As and Cr were higher than permissible limits in *T. mediterraneus*, while Pb, Cd, As, and Cr were higher in *M. merlangus*. Arsenic concentrations were higher than the maximum limits in both *T. mediterraneus* and *M. merlangus*.

Table 5 Permissible content of heavy metals in fish (mg kg^{-1})

	mg kg^{-1}				
	TKB	EPA	WHO	*T. mediterraneus*	*M. merlangus*
Pb	0.3		0.5	0.4	0.7
Cd	0.05	1.4	0.5	0.2	0.7
As	1		1.8	15.7	23.9
Cr		4.1	0.15	0.2	0.3
Hg	0.5		0.5	0.3	0.2
Cu		54	30	1.2	0.4
Zn		410	30	17.7	14.8
Fe		410	100	43.5	38.9

TKB Turkish Fisheries Laws and Regulations, *EPA* Environmental Protection Agency, *WHO* World Health Organization

The cadmium concentrations in *T. mediterraneus* ranged from 0.3 to 2.8 mg kg^{-1} and 0.2 to 22.3 mg kg^{-1} in *M. merlangus*. These results correspond with the results of Pekey (2006). In his study, he found As, Cd, Pb and Zn elements in high concentrations in the northern part of Izmit Bay. However, Cucu et al. (2019) reported that in 2013 the mean values for Cd from the Gebze region near 2.st were 2.2 µg kg^{-1} and 0.22 µg kg^{-1} for *T. mediterraneus* and *M. merlangus*, respectively which is very low when compared to our findings. It was determined that in the Gulf of Gemlik which is one of the most industrialized and contaminated regions in Turkey, *T. mediterraneus* and *M. merlangus* both had high Cd concentrations with 1 mg kg^{-1} and this exceeded the permissible limits determined by WHO (Ünlü et al. 2008; Kayhan et al. 2017). In the Aegean Sea, these concentrations were lower than 0.01−0.04 mg kg $^{-1}$ (Dalman et al. 2006). It is widely known that Cd is found in trace concentrations in marine environments and aquatic

Table 6 Estimated weekly intakes (EWI) of *T. mediterraneus* and *M. merlangus*

		Cr	Fe	Cu	Zn	As[a]	Cd	Pb	Hg
T. mediterraneus (EWI mg/week/ 70 kg bw)	1.st	0.28	19.5	1.33	21.3	0.3	0.35	0.34	ND
	2.st	0.11	23.5	1.23	24.5	0.8	0.23	0.24	0.09
	3.st	0.20	41.6	1.57	32.7	1.6	0.45	0.64	0.64
	4.st	0.30	35	3.10	32.8	0.9	0.36	0.53	0.05
M. merlangus (EWI mg/week/ 70 kg bw)	1.st	0.45	23.97	0.48	16.02	1.3	0.43	0.39	0.02
	2.st	0.30	77.65	0.54	17.71	0.8	ND	1.81	0.05
	3.st	0.39	40.50	0.67	28.56	0.96	0.73	0.17	0.03
	4.st	0.69	28.63	0.48	20.37	1.2	3.27	0.62	0.07
Guidelines for PTWI (mg/week/kg)		0.02	5.6	3.5	7	0.02	0.01	0.03	0.004
PTWI (mg/week/ 70 kg bw)		1.63	392	245	490	1.05	0.49	1.75	0.28

EWI estimated weekly intake, *PTWI* provisional tolerable weekly intake

[a]Total arsenic concentrations were converted to inorganic arsenic

organisms. In this study, mean cadmium concentrations for both species were found to be higher than Turkish Fisheries Laws and Regulations and lower than the WHO values. Castro-González and Méndez-Armenta (2008) stated that Cadmium negatively affects vital organs: brain, kidney, lung, bones, and the central nervous system. Previous studies showed that in the Marmara Sea cadmium concentrations in *Merluccius merluccius* varied between 0.01 and 2.14 mg kg^{-1}, considerably lower than our results. Although the heavy metal concentrations in fish are affected by their diet, the age of fish and physicochemical properties of water, these results may be associated with increased cadmium pollution in the Marmara Sea (Afshan et al. 2014; Pandey et al. 2008).

T. mediterraneus and *M. merlangus* had a lower concentration of Cu than national and international limits. For fish samples from Saroz Bay, Güngör and Kara (2018) also detected Cu levels of 0.73 and 0.28 mg kg^{-1}, respectively. At 4. St near Saroz Bay, the mean Cr concentration in *T. mediterraneus* was 2.0 mg kg^{-1}. In Tekirdağ province, urbanization and industry are widespread and the coastal area is heavily affected by pollution (Dökmeci et al. 2019).

To assess the human health risk from heavy metals in fish, it is important to have knowledge of the dietary intake of metals and their synergistic effects. For this reason, the EWI for a 70 kg body weight of an adult person was determined based on the results of the present study in comparison with Provisional Tolerable Weekly Intake (PTWI) which were established by The Joint FAO/WHO Expert Committee on Food Additives (Table 6; FAO/WHO 2004). The results indicated that for Cr, Fe, Cu, and Zn, there is no adverse health risk from the consumption of these two species. Although As, Cd, Pb, and Hg were at relatively higher levels than the PTWI, this could potentially cause adverse effects and toxicity (Marcotrigiano and Storelli 2003; Castro-González and Méndez-Armenta 2008). Lead, cadmium, and mercury are heavy metals that do not naturally occur in living organisms and their function in human body is still unknown (Lenntech Water Treatment and Air Purification 2004). Therefore uptake of these metals at low concentrations can be very harmful. These heavy metals could be toxic, neurotoxic, carcinogenic, or mutagenic (Duruibe et al. 2007).

The FAO/WHO Expert Committee on Food Additives reported that due to the long half-life of Cd, it does not have a significant effect concerning the overall exposure from daily food intake (Saei-Dehkordi and Fallah 2011). Inorganic arsenic compounds are more acutely toxic than organic forms, and EWI values calculated as inorganic arsenic and especially from Site 3, were higher than the guidelines (1.05 mg/week/70 kg bw).

Lead concentrations in *M. merlangus* ranged from 0.01 to 3.1 mg kg^{-1} and 0.05 to 8.14 mg kg^{-1} for *T. mediterraneus*. Mean lead concentrations for both species were found to be higher than Turkish Fisheries Laws and Regulations. In 2013, lead concentrations were reported at 4.5 µg kg^{-1} for *T. mediterraneus* and 0.23 µg kg^{-1} for *M. merlangus* in the Marmara Sea (Cucu et al. 2019). Compared to the Black, Aegean, and Mediterranean seas, *T. mediterraneus* had lower Pb concentrations (Türkmen et al. 2008b). *Merlangius merlangus* also had higher lead concentrations than WHO guidelines. Aksu et al. (2011) determined that in *M. merluccius* which is a demersal fish like *M. merlangus*, Pb concentrations ranged between 3.23 and 10.5 mg kg^{-1} but our results were higher than the Southern Black Sea Shelf which was found to be 0.05–5.75 mg kg^{-1} for *M. merluccius* (Aksu et al. 2011).

Mercury concentrations in *T. mediterraneus* ranged from 0.007 to 1.24 mg kg^{-1} and 0.008 to 0.51 mg kg^{-1} in *M. merlangus*. Mean mercury levels were found to be lower than permissible limits. The results showed that the mean values of Hg were the lowest at sites 1 and 4 for *T. mediterraneus*. In general, although the results were below permissible limits, Site 3 results were very close to the limit values for both fish species. As it is well known, Hg may have toxic effects on the digestive, immune, and nervous systems (Bhardwaj et al. 2009; Li et al. 2010; Rice et al. 2014).

Arsenic concentrations in both species were found to be very high. In *T. mediterraneus* total As varied between 3.2 and 49.9 mg kg^{-1} and in *M. merlangus* 8–52.9 mg kg^{-1}. In a study by Güngör and Kara (2018), in Saroz Bay, As concentrations for *T. mediterraneus* and *M. merlangus* were found to be 1.23 and 3.6 mg kg^{-1}, respectively. Dökmeci et al. 2019 reported that in Tekirdağ province As concentrations in sediment samples were determined as being highly polluted in accordance with the EPA sediment quality guidelines (EPASQG). High As concentrations in fish samples could be the result of heavy metal loads in sediment. For both species, the maximum levels were determined at Site 3 where the pollutants were related to anthropogenic inputs from İzmit Bay. Studies have shown that exposure to arsenic is caused by cancer, cardiovascular disease, neurological disorders, and dermal effects (Miller et al. 2002; Vahidnia et al. 2007; De Vizcaya-Ruiz et al. 2009).

The lowest and highest iron levels in *T. mediterraneus* were 8.6–102.9 mg kg^{-1} and 9.5–51.5 mg kg^{-1} in *M. merlangus*. Iron showed the highest metal level in both species and Site 3 had the highest concentrations of Fe. Due to being a pelagic fish *T. mediterraneus* feed at higher trophic levels and these predatory fish contained significantly higher concentrations of Fe and Zn (Afandi et al. 2018). In previous studies, the Fe concentrations in *M. merlangus* in Marmara, Mediterranean, and Black seas were 5.0, 6.8, and 4.5 mg kg^{-1}, respectively, which were 10 times lower than our results (Turan et al. 2009). Similarly, with Zn concentrations, *M. merlangus* in the Mediterranean and Black seas were 5.3 and 6.5 mg kg^{-1}, respectively which were lower than our results (Turan et al. 2009; Güngör and Kara 2018).

Generally, environmental contaminants are present together (Borgmann et al. 2008; Naz and Javed 2013). Toxicity tests indicate that metal combinations are usually more toxic than single metals (Marr et al. 1998; Verma et al. 1982). Studies showed that some fish species are less sensitive to heavy metal mixtures such as Cu, Zn, Cr, and Fe according to the stage of fish development (Kazlauskiene and Stasiunaite 1999; Vosylienė et al. 2003). Batool and Javed (2015) reported that a combination of heavy metals revealed a synergistic effect. Heavy metal combinations affect public health as well as fish species. Groten et al. (1997) demonstrated that arsenic-lead combination could cause changes in rats. Also, lead-mercury mixtures act synergistically which are extremely neurotoxic and exhibit more toxic than the single one (Wildemann et al. 2015). While conducting the risk assessment for public health, because of all these adverse effects of heavy metal combinations, toxicity tests and synergistic interactions should be investigated.

Conclusion

This study provides additional data on the heavy metal content of two economic fish in Turkey. Results are essential in risk assessment of consumer exposure to heavy metals. The Provisional Tolerable Weekly Intake of As, Cd, Pb, and Hg was higher than the safe limits. Results showed that both pelagic and demersal fish species contain heavy metals above recommended limits and precautions need to be taken urgently to reduce pollution in the Marmara Sea. Heavy metal accumulation in fish muscle tissue should be considered as an important warning both for fish health and human health via consumption. To assess the risk to human health based on heavy metal concentrations in fish species, periodical monitoring is necessary.

Acknowledgements This study was supported by TUBİTAK with the project number 116S520. We would like to thank Zeynep DORAK for providing assistance in statistical analysis.

Funding This study was supported by TUBİTAK with the project number 116S520.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

Afandi I, Talba S, Benhra A, Benbrahim S, Chfiri R, Labonne M et al. (2018) Trace metal distribution in pelagic fish species from the north-west African coast (Morocco). Int Aquat Res 10 (2):191–205. https://doi.org/10.1007/s40071-018-0192-7

Afshan S, Ali S, Ameen US, Farid M, Bharwana SA, Hannan F, Ahmad R (2014) Effect of different heavy metal pollution on fish. Res J Chem Environ Sci 2(1):74–79

Aksu A, Balkis N, Taşkin ÖS, Erşan MS (2011) Toxic metal (Pb, Cd, As and Hg) and organochlorine residue levels in hake (Merluccius merluccius) from the Marmara Sea, Turkey. Environ Monit Assess 182(1–4):509–521. https://doi.org/10.1007/s10661-011-1893-1

Alkan N, Alkan A, Gedik K, Fisher A (2016) Assessment of metal concentrations in commercially important fish species in Black Sea. Toxicol Ind Health 32(3):447–456

Anonymous (2005) T.C. Tarım ve Köyişleri Bakanlığından Su Ürünleri Yönetmeliği. 09.08.2005 tarihli Resmi Gazete No: 25901

Barak NA, Mason CF (1990) Mercury, cadmium and lead in eels and roach: the effects of size, season and locality on metal concentrations in flesh and liver. Sci Total Environ 92:249–256

Barone G, Giacominelli-Stuffler R, Storelli MM (2013) Comparative study on tracemetal accumulation in the liver of two fish species

(Torpedinidae): concentration-size relationship. Ecotoxicol Environ Saf 97:73–77. https://doi.org/10.1016/j.ecoenv.2013.07.004
Batool U, Javed M (2015) Synergistic effects of metals (cobalt, chromium and lead) in binary and tertiary mixture forms on Catla catla, Cirrhina mrigala and Labeo rohita. Pak J Zool 47 (3):617–623
Berik N, Kahraman N (2012) Element contents of spiny dogfish (*Squalus acanthias* l., 1758) from the Marmara Sea (Turkey). Fresenius Environ Bull 21–2:276–281
Bhardwaj A, Kar JP, Thakur OP, Srivastava P, Sehgal HK (2009) Electrical characteristics of PbSe nanoparticle/Si heterojunctions. J Nanosci Nanotechnol 9(10):5953–5957. https://doi.org/10.1166/jnn.2009.1254
Bilandzic N, Ǒokic M, Sedak M (2011) Metal content determination in four fish species from the Adriatic Sea. Food Chem 124:1005–1010. https://doi.org/10.1016/j.foodchem.2010.07.060
Borgmann K, Hoeller U, Nowack S, Bernhard M, Röper B, Brackrock S, Alberti W et al. (2008) Individual radiosensitivity measured with lymphocytes may predict the risk of acute reaction after radiotherapy. Int J Radiat Oncol Biol Phys 71(1):256–264
Burada A, Teodorof L, Despina C, Seceleanu-Odor D, Tudor M, Ibram O, Tudor M et al. (2017) Trace elements in fish tissue with commercial value of the Danube Delta Biosphere Reserve. Environ Eng Manag J 16(3):731–738
Canlı M, Furness RW (1993) Toxicity of heavy metals dissolved in sea water and influences of sex and size on metal accumulation and tissue distribution in the Norway lobster Nephrops norvegicus. Mar Environ Res 36:217–236. https://doi.org/10.1016/0141-1136(93)90090-M
Canlı M, Atlı G (2003) The relationships between heavy metal (Cd, Cr, Cu, Fe, Pb, Zn) levels and the size of six Mediterranean fish species. Environ Pollut 121(1):129–136. https://doi.org/10.1016/S0269-7491(02)00194-X
Carolin CF, Kumar PS, Saravanan A, Joshiba GJ, Naushad M (2017) Efficient techniques for the removal of toxic heavy metals from aquatic environment: a review. J Environ Chem Eng 5 (3):2782–2799
Castro-González MI, Méndez-Armenta M (2008) Heavy metals: Implications associated to fish consumption. Environ Toxicol Pharmacol 26(3):263–271. https://doi.org/10.1016/j.etap.2008.06.001
Censi P, Spoto SE, Saiano F, Sprovieri M, Mazzola S, Nardone G et al. (2006) Heavy metals in coastal water systems. A case study from the northwestern Gulf of Thailand. Chemosphere 64(7):1167–1176. https://doi.org/10.1016/j.chemosphere.2005.11.008
Chamberlain I, Adams K, Le S (2000) ICP-MS determination of trace elements in fish. At Spectrosc 21(4):118–122
Clarkson TW (1998) Human toxicology of mercury. J Trace Elem Exp Med 11(2–3):303–317. https://doi.org/10.1002/(SICI)1520-670X(1998)11:2/33.0.CO;2-V
Coelhan M, Strohmeier J, Barlas H (2006) Organochlorine levels in edible fish from the Marmara Sea, Turkey. Environ Int 32 (6):775–780. https://doi.org/10.1016/j.envint.2006.03.015
Council of Europe (2001) Council of Europe's policy statements concerning materials and articles intended to come into contact with foodstuffs. Policy Statement concerning materials and alloys. Technical Document, Guidelines on metals and alloys used as food contact materials (09.03.2001), Strasbourg. p. 67
Cucu AK, Topkaya M, Erdogan G, Aboul-Enein HY (2019) Quantitative determination of heavy metal contamination in horse mackerel and whiting caught in the sea of Marmara. Bull Environ Contamination Toxicol 102(4):498–503. https://doi.org/10.1007/s00128-019-02574-5
Dalman O, Demirak A, Balcı A (2006) Determination of heavy metals (Cd, Pb) and trace elements (Cu, Zn) in sediments and fish of the Southeastern Aegean Sea (Turkey) by atomic absorption spectrometry. Food Chem 95:157–162. https://doi.org/10.1016/j.foodchem.2005.02.009
Demirkol O, Aktaş N (2002) Tekirdağ açıklarından ve İzmit körfezi'nden avlanan İstavrit (*Trachurus trachurus* L., 1758) balıklarında ağır metal birikimi üzerine bir araştırma. Mühendislik bilimleri Derg 8(2):205–209
De Vizcaya-Ruiz A, Barbier O, Ruiz-Ramos R, Cebrian ME (2009) Biomarkers of oxidative stress and damage in human populations exposed to arsenic. Mutat Res/Genet Toxicol Environ Mutagenesis 674(1–2):85–92
Dökmeci AH, Sabudak T, Dalmış V (2019) Accumulation of essential and toxic metals in sediment from the Marmara Sea along Tekirdağ coast: risk assessment for ecological health. Desalination Water Treat 169:166–172. https://doi.org/10.5004/dwt.2019.24671
Duruibe JO, Ogwuegbu MOC, Egwurugwu JN (2007) Heavy metal pollution and human biotoxic effects. Int J Phys Sci 2(5):112–118
Elder JF, Collins JJ (1991) Freshwater molluscs as indicators of bioavailability and toxicity of metals in surface systems. Rev Environ Contam Toxicol 122:37–79
Endo T, Hisamichi Y, Haraguchi K, Kato Y, Ohta C, Koga N (2008) Hg, Zn and Cu levels in the muscle and liver of tiger sharks (*Galeocerdo cuvier*) from the coast of Ishigaki Island, Japan: relationship between metal concentrations and body length. Mar Pollut Bull 56:1774–1780. https://doi.org/10.1016/j.marpolbul.2008.06.003
Ergül HA, Aksan S, İpşiroğlu M (2018) Assessment of the consecutive harmful dinoflagellate blooms during 2015 in the Izmit Bay (the Marmara Sea). Acta Oceanol Sin 37(8):91–101. https://doi.org/10.1007/s13131-018-1191-7
European Food Safety Authority (EFSA) Panel on Contaminants in the Food Chain (CONTAM), (2010). Scientific Opinion on Lead in Food
European Food Safety Authority (EFSA) (2012a) Cadmium dietary exposure in the European population. EFSA J 10(1):2551
European Food Safety Authority (EFSA) Panel on Contaminants in the Food Chain (CONTAM) (2012b) Scientific Opinion on the risk for public health related to the presence of mercury and methylmercury in food. EFSA J 10(12):2985
EPA (1989) Assessing Human Health Risks from Chemically Contaminated Fish and Shellfish: A Guidance Manual. EPA-503/8-89-002, US Environmental Protection Agency. Office of Research and Development, Washington DC
FAO/WHO (2004) Summary of evaluations performed by the joint FAO/WHO expert committee on food additives (JECFA 1956e2003). ILSI Press International Life Sciences Institute
FAO/WHO (2010) Summary report of the seventy-third meeting of JECFA. Joint FAO/WHO Expert Committee on Food Additives, Geneva
Gao X, Li P (2012) Concentration and fractionation of trace metals in surface sediments of intertidal Bohai Bay, China. [Research Support, Non-U.S. Gov't]. Mar. Pollut. Bull 64(8):1529–1536. https://doi.org/10.1016/j.marpolbul.2012.04.026
Groten JP, Schonen ED, Bladeren PJ, Kuper CF, Zorge JA, Feron VJ (1997) Subacue toxicity of a mixture of nine chemicals in rats: detecting interactive effects with a fractionated two-level factorial design. Fundam Appl Toxicol 36:15–29. https://doi.org/10.1006/faat.1996.2281
Guhathakurta H, Kaviraj A (2000) Heavy metal concentration in water, sediment, shrimp (*Penaeus monodon*) and mullet (*Liza parsia*) in some brackish water ponds of Sunderban, India. Mar Pollut Bull 40(11):914–920. https://doi.org/10.1016/S0025-326X(00)00028-X
Gümgüm B, Ünlü E, Tez Z, Gülsün Z (1994) Heavy metal pollution in water, sediment and fish from the Tigris River in Turkey. Chemosphere 29:111–116

Güngör A, Kara D (2018) Toxicities and risk assessment of heavy metals of the six most consumed fish from the Marmara Sea. Environ Sci Pollut Res 25(3):2672–2682. https://doi.org/10.1007/s11356-017-0672-0
Heath AG (1995) Water Pollution and Fish Physiology. CRC press, Florida, USA
Hu B, Li G, Li J, Bi J, Zhao J, Bu R (2013) Spatial distribution and ecotoxicological risk assessment of heavy metals in surface sediments of the southern Bohai Bay, China. Environ Sci Pollut Res 20 (6):4099–4110. https://doi.org/10.1007/s11356-012-1332-z
Kayhan F, Büyükurganci N, Kaymak G (2017) Accumulation of cadmium and lead in commercially important fish species in the Gulf of Gemlik, Marmara Sea, Turkey. Aquat Sci Eng 32 (4):178–183. https://doi.org/10.18864/TJAS201716
Kazlauskiene N, Stasiunaite P (1999) The lethal and sublethal effect of heavy metal mixture on rainbow trout (*Oncorhynchus mykiss*) in its early stages of development. Acta Zoologica Lituanica 9 (2):47–55
Keskin Y, Baskaya R, Özyaral O, Yurdun T, Lüleci NE, Hayran O (2007) Cadmium, lead, mercury and copper in fish from the Marmara Sea, Turkey. Bull Environ Contam Toxicol 78:258–261
Lee JW, Choi H, Hwang UK, Kang JC, Kang YJ, Kim KI, Kim JH (2019) Toxic effects of lead exposure on bioaccumulation, oxidative stress, neurotoxicity, and immune responses in fish: a review. Environ Toxicol Pharmacol 68:101–108
Lenntech Water Treatment and Air Purification (2004) Water Treatment, Published by Lenntech, Rotterdamseweg, Netherlands (www.excelwater.com/thp/filters/Water-Purification.htm)
Li SJ, Zhang SH, Chen HP, Zeng CH, Zheng CX, Li LS, Liu ZH (2010) Mercury-induced membranous nephropathy: clinical and pathological features. Clin J Am Soc Nephrol 5(3):439–444. https://doi.org/10.2215/CJN.07571009
Liang Y, Cheung RYH, Wong MH (1999) Reclamation of wastewater for polyculture of freshwater fish: bioaccumulation of trace metals in fish. Water Res 33:2690–2700. https://doi.org/10.1016/S0043-1354(98)00473-4
Marcotrigiano GO, Storelli MM (2003) Heavy metal, polychlorinated biphenyl and organochlorine pesticide residues in marine organisms: risk evaluation for consumers. Vet Res Commun 27(1):183–195. https://doi.org/10.1023/B:VERC.0000014137.02422.f4
Marr JCA, Hansen JA, Meyer JS, Cacela D, Podrabsky T, Lipton J, Bergman HL (1998) Toxicity of cobalt and copper to rainbow trout: application of a mechanistic model for predicting survival. Aquat Toxicol 43(4):225–238
Mataveli LRV, Arauz LJD, Carvalho MDFH, Tiglea P (2013) Validation of methodology for determining As, Pb and Cd in fish by using ICP-MS: Preliminary studies. Rev. Inst. Adolfo Lutz 72 (4):332–335
Miller WH, Schipper HM, Lee JS, Singer J, Waxman S (2002) Mechanisms of action of arsenic trioxide. Cancer Res 62 (14):3893–3903
Miri M, Akbari E, Amrane A, Jafari SJ, Eslami H, Hoseinzadeh E et al. (2017) Health risk assessment of heavy metal intake due to fish consumption in the Sistan region, Iran. Environ Monit Assess 189(11):583. https://doi.org/10.1007/s10661-017-6286-7
Monterio LR, Lopes HD (1990) Mercury content of swordfish, *Xiphias fladius*, in relation to length, weight, age and sex. Mar Pollut Bull 21:293–296
Munoz-Olivas R, Camara C (2001) Speciation related to human health. In: Ebdon L, Pitts L, Cornelis R, Crews H, Donard OFX, Quevauviller P (Eds) Trace element speciation for environment, food and health. The Royal Society of Chemistry, Cambridge, pp 331–353
Mziray P, Kimirei IA (2016) Bioaccumulation of heavy metals in marine fishes (Siganus Sutor, Lethrinus Harak, and Rastrelliger Kanagurta) from Dar es salaam Tanzania. Regional Stud Mar Sci 7:72–80. https://doi.org/10.1016/j.rsma.2016.05.014
Naccari C, Cicero N, Ferrantelli V, Giangrosso G, Vella A, Macaluso A, Dugo G et al. (2015) Toxic metals in pelagic, benthic and demersal fish species from Mediterranean FAO zone 37. Bull Environ contamination Toxicol 95(5):567–573
National Academy of Science (1989) Recommended dietary allowances, 10th edn, National Academy Press, Washington, D.C., p. 298
Naz S, Javed M (2013) Growth responses of fish during chronic exposure of metal mixture under laboratory conditions. Pak Veterinary J 33(3):354–357
Nussey G, Van Vuren JHJ, du Preez HH (2000) Bioaccumulation of chromium, manganese, nickel and lead in the tissues of the moggel, Labeo umbratus (Cyprinidae), from Witbank dam, Mpumalanga. Water Sa 26:269–284
Okay OS, Egesel L, Tüfekçi V, Morkoç E, Gaines A (1998) Investigation of three wastewaters entering Izmit Bay (Turkey) by means of batch and chemostat culture algal bioassays. Mar Environ Res 46(1–5):283–288. https://doi.org/10.1016/S0141-1136(97)00115-3
Olaifa FE, Olaifa AK, Onwude TE (2004) Lethal and sub-lethal effects of copper to the African catfish (*Clarias gariepinus*) juveniles. Afr J Biomed Res, 7(2). https://doi.org/10.4314/ajbr.v7i2.54071
Özden Ö, Erkan N (2016) Evaluation of risk characterization for mercury, cadmium, lead and arsenic associated with seafood consumption in Turkey. Expo Health 8:43–52
Pandey S, Parvez S, Ansari RA, Ali M, Kaur M, Hayat F et al. (2008) Effects of exposure to multiple trace metals on biochemical, histological and ultrastructural features of gills of a freshwater fish, Channa punctata Bloch. Chem-Biol Interact 174 (3):183–192. https://doi.org/10.1016/j.cbi.2008.05.014
Pekey H, Karakuş D, Bakoğlu M (2004) Source apportionment of trace metals in surface waters of a polluted stream using multivariate statistical analyses. Mar Pollut Bull 49:809–818. https://doi.org/10.1016/j.marpolbul.2004.06.029
Pekey H (2006) Heavy metal pollution assessment in sediments of the İzmit Bay, Turkey. Environ Monit Assess 123:219–231. https://doi.org/10.1007/s10661-006-9192-y
Predescu C, Vlad G, Matei E, Predescu A, Sohaciu M, Coman G (2017) Methods for heavy metals (hm) extraction from sludge samples and their use for soil upgrading. Environ Eng Manag J 16:2469–2474
Rejomon G, Nair M, Joseph T (2010) Trace metal dynamics in fishes from the southwest coast of India. Environ Monit Assess 167:243–255
Rice KM, Walker EM Jr, Wu M, Gillette C, Blough ER (2014) Environmental mercury and its toxic effects. J Preventive Med Public Health 47(2):74. https://doi.org/10.3961/jpmph.2014.47.2.74
Roesijadi G, Robinson WE (1994) Metal regulation in aquatic animals: mechanism of uptake, accumulation and release. In: Malins, DC, Ostrander, GK (Eds.) Aquatic toxicology (Molecular, Biochemical and Cellular Perspectives. Lewis Publishers, London
Saei-Dehkordi SS, Fallah AA (2011) Determination of copper, lead, cadmium and zinc content in commercially valuable fish species from the Persian Gulf using derivative potentiometric stripping analysis. Microchem J 98(1):156–162. https://doi.org/10.1016/j.microc.2011.01.001
Stergiou KI, Karpouzi VS (2002) Feeding habits and trophic levels of Mediterranean fish. Rev Fish Biol Fish 11(3):217–254
Topcuoğlu S, Güven KC, Balkıs N, Kırbaşoğlu Ç (2003) Heavy metal monitoring of marine algae from the Turkish Coast of the Black Sea, 1998–2000. Chemosphere 52(10):1683–1688
TUIK (2017) Turkish Fishery Statistics, http://www.tuik.gov.tr/
TUIK (2018) Turkish Fishery Statistics, http://www.tuik.gov.tr/

Turan C, Dural M, Oksuz A, Öztürk B (2009) Levels of heavy metals in some commercial fish species captured from the Black Sea and Mediterranean coast of Turkey. Bull Environ Contamination Toxicol 82(5):601–604. https://doi.org/10.1007/s00128-008-9624-1

Türkmen M, Türkmen A, Tepe Y, Ateş A, Gökkuş K (2008a) Determination of metal contaminations in sea foods from Marmara, Aegean and Mediterranean seas: twelve fish species. Food Chem 108:794–800

Türkmen M, Türkmen A, Tepe Y (2008b) Metal contaminations in five fish species from Black, Marmara, Aegean and Mediterranean seas, Turkey. J Chil Chem Soc 53(1):1424–1428. https://doi.org/10.4067/S0717-97072008000100021

Türkmen A, Tepe Y, Türkmen M (2008c) Metal levels in tissues of the European anchovy, Engraulis encrasicolus L., 1758, and picarel, Spicara smaris L., 1758, from Black, Marmara and Aegean Seas. Bull Environ Contamination Toxicol 80(6):521–525

Türkmen M, Türkmen A, Tepe Y, Töre Y, Ateş A (2009) Determination of metals in fish species from Aegean and Mediterranean seas. Food Chem 113(1):233–237. https://doi.org/10.1016/j.foodchem.2008.06.071

Türksönmez Ç, Diler A (2019) Seasonal determination of heavy metal levels of anchovy (*Engraulis encrasicolus* L., 1758) obtained from the Marmara Sea. Acta Biologica Turc 32(4):242–247

Ünlü S, Topçuoğlu S, Alpar B, Kırbaşoğlu Ç, Yılmaz YZ (2008) Heavy metal pollution in surface sediment and mussel samples in the Gulf of Gemlik. Environ Monit Assess 144(1–3):169. https://doi.org/10.1007/s10661-007-9986-6

Vahidnia A, Van der Voet GB, De, Wolff FA (2007) Arsenic neurotoxicity—a review. Hum Exp Toxicol 26(10):823–832

Verma SR, Jain M, Dalela RC (1982) A laboratory study to assess separate and in-combination effects of zinc, chromium and nickel to the fish Mystus vittatus. Acta Hydrochimica et Hydrobiologica 10(1):23–29

Vosylienė MZ, Kazlauskienė N, Svecevičius G (2003) Effect of a heavy metal model mixture on biological parameters of rainbow trout Oncorhynchus mykiss. Environ Sci Pollut Res 10 (2):103–107

Wagner A, Boman J (2003) Biomonitoring of trace elements in muscle and liver tissue of freshwater fish. Spectrochimica Acta Part B 58:2215–2226

Weber P, Behr ER, Knorr CDL, Vendruscolo DS, Flores EM, Dressler VL, Baldisserotto B (2013) Metals in the water, sediment, and tissues of two fish species from different trophic levels in a subtropical Brazilian river. Microchem J 106:61–66

WHO (1989) World Health Organization, Evaluation of certain food additives and the contaminants mercury, lead and cadmium. WHO Technical Report Series No: 505

WHO (1996) Trace elements in human nutrition and health. ISBN 92 4 156173 4 (NLM Classification: QU 130), Geneva

Widianarko B, Van Gestel CAM, Verweij RA, Van Straalen NM (2000) Associations between trace metals in sediment, water, and guppy, Poecilia reticulata (Peters), from urban streams of Semarang, Indonesia. Ecotox Environ Safe 46:101–107. https://doi.org/10.1006/eesa.1999.1879

Wildemann TM, Weber LP, Siciliano SD (2015) Combined exposure to lead, inorganic mercury and methylmercury shows deviation from additivity for cardiovascular toxicity in rats. Appl Toxicol 35:918–926. https://doi.org/10.1002/jat.3092

Zeitoun MM, Mehana EE (2014) Impact of water pollution with heavy metals on fish health: overview and updates. Glob Veterinaria 12 (2):219–231

Zhao Z, Zhang L, Cai Y, Chen Y (2014) Distribution of polycyclic aromatic hydrocarbon (PAH) residues in several tissues of edible fishes from the largest freshwater lake in China, Poyang Lake, and associated human health risk assessment. Ecotoxicol Environ Saf 104:323–331. https://doi.org/10.1016/j.ecoenv.2014.01.037