

Heavy Metal Contamination in Marine Fish from Turkish Seas: A Systematic Review of Spatial Patterns, Trophic Transfer, and Human Health Risks

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Systematic Review

Keywords: Heavy metals, marine fish, Turkish seas, mercury, cadmium, lead, bioaccumulation, human health risk, microplastics

Posted Date: September 4th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10898207/v1>

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Additional Declarations: No competing interests reported.

Abstract

The presence of toxic metals in marine fish represents a significant environmental and public health issue owing to their persistence, tendency to bioaccumulate, and ability to biomagnify within aquatic food webs. This review synthesizes current knowledge on heavy metal contamination in commercially harvested fish species from the Turkish seas, focusing on spatial distribution, bioaccumulation patterns, trophic transfer, and potential human health risks. Publications published between January 2003 and March 2025 were identified through a systematic literature search using the Web of Science, Scopus, and Google Scholar databases. A total of 59 peer-reviewed studies investigating mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and other trace elements in marine fish from the Black Sea, Sea of Marmara, Aegean Sea, and Mediterranean Sea were evaluated. The reviewed studies showed considerable regional variability in heavy metal concentrations. Higher Pb and Cd concentrations were reported from the Sea of Marmara, whereas elevated mercury accumulation was observed in predatory fish from the Aegean and Mediterranean Seas. Estimated daily intake (EDI), target hazard quotient (THQ), and hazard index (HI) values generally remained below internationally accepted safety thresholds for the general population; however, higher exposure may occur among frequent fish consumers and sensitive groups, including children and pregnant women. Microplastic–metal interactions and climate-related changes in contaminant bioavailability are discussed as potential factors influencing future risks. Methodological differences among studies limit direct comparisons, indicating the need for harmonized monitoring strategies and standardized health risk assessment approaches in Türkiye.

1. Introduction

Heavy metals constitute a class of persistent environmental pollutants that resist natural degradation processes (Järup, 2003). Once released into aquatic systems, they accumulate in organisms and undergo biomagnification through trophic chains (Bat et al., 2009; Briffa et al., 2020; FAO, 2022; Järup, 2003). Consequently, even relatively low environmental concentrations may lead to elevated metal burdens in marine organisms, posing potential threats to ecosystem health, biodiversity, and human populations consuming contaminated seafood (Bat et al., 2009; Briffa et al., 2020; Çamur et al., 2021; Mozaffarian and Rimm, 2006).

Marine environments, particularly coastal and semi-enclosed basins, are exposed to pollutants originating from a variety of human activities, including industrial discharges, agricultural runoff, municipal wastewater, shipping activities, and atmospheric deposition (Çamur et al., 2021; FAO, 2022; Tüzen, 2003). Metals adsorb onto suspended particles and accumulate in bottom sediments, where they may persist for long periods. Sediments therefore function not only as sinks but also as secondary sources of contamination, as metals can be remobilized through physical disturbances, chemical changes, or biological processes, resulting in prolonged environmental exposure (Tüzen, 2003; Wang and Rainbow, 2008).

Fish play a pivotal role in aquatic food webs and represent a primary source of high-quality animal protein for human populations, essential fatty acids, vitamins, and trace elements for human nutrition (Çamur et al., 2021; Tüzen, 2003; Türkmen et al., 2008; Bosch et al., 2016). At the same time, fish are widely recognized as effective bioindicators for monitoring marine pollution because metal accumulation varies according to species-specific ecological characteristics such as habitat preference, trophic level, feeding behavior, age, growth rate, and longevity (Bosch et al., 2015; Türkmen et al., 2008; Genç, 2021). Since seafood consumption represents one of the primary pathways of human exposure to toxic metals, monitoring metal concentrations in edible fish tissues has become an important component of environmental surveillance and public health risk assessment (Demirtaş et al., 2024; Mendil et al., 2010; Köker et al., 2021).

Türkiye is surrounded by four geographically and ecologically distinct marine basins—the Black Sea, the Sea of Marmara, the Aegean Sea, and the Mediterranean Sea. These seas differ substantially in their hydrographic characteristics, water circulation patterns, biological productivity, and intensity of anthropogenic activities, resulting in considerable spatial variability in contaminant inputs and environmental quality (Çamur et al., 2021; Türkmen et al., 2009; Dalman et al., 2006; Alkan et al., 2016). The Sea of Marmara, located between the Black Sea and the Aegean Sea, is exposed to intensive industrialization, dense maritime transportation, urbanization, and domestic wastewater discharges. In contrast, the Black Sea receives substantial riverine inputs from a large international drainage basin, whereas the Aegean and Mediterranean Seas are influenced by distinct hydrodynamic conditions, tourism-related activities, fisheries, and localized industrial development (FAO, 2022; Türkmen et al., 2009; Dalman et al., 2006; Alkan et al., 2016).

These differences make Turkish marine ecosystems particularly suitable for examining regional patterns of metal contamination and accumulation in marine fish.

Over the past two decades, numerous investigations have examined heavy metal concentrations in marine fish species collected from Turkish waters (Alkan et al., 2016; Copat et al., 2018; Dalman et al., 2006; Bat and Özkan, 2019; Kayhan et al., 2017; Lavoie et al., 2013; Mendil et al., 2010; Türkmen et al., 2009; Wang and Rainbow, 2008). These studies have provided valuable information regarding regional contamination patterns, species-specific accumulation characteristics, and potential implications for seafood safety. Nevertheless, direct comparisons among studies remain difficult because of considerable methodological heterogeneity, including differences in sampling locations, fish species, biological tissues analyzed, analytical techniques, quality assurance procedures, detection limits, and reporting units (Ali and Khan, 2019; Güngör and Kara, 2018; Kayhan et al., 2017; Ateş et al., 2015). Such inconsistencies complicate the evaluation of temporal trends, limit nationwide comparisons, and hinder the development of harmonized monitoring strategies and evidence-based environmental management policies.

Several review articles have examined heavy metal contamination in aquatic organisms from global or regional perspectives, with particular emphasis on bioaccumulation mechanisms, trophic transfer,

environmental behavior, and human health implications (Artar et al., 2024; Bosch et al., 2016; Burger and Gochfeld, 2005; Türkmen et al., 2008; Ali and Khan, 2019). However, to the best of our knowledge, no review has comprehensively synthesized the available evidence on heavy metal contamination in marine fish across all four Turkish seas while simultaneously integrating regional distribution patterns, bioaccumulation characteristics, trophic transfer processes, and human health risk assessments. A comprehensive evaluation of the available evidence may contribute to a better understanding of contamination dynamics in Turkish marine ecosystems.

In addition to conventional sources of contamination, emerging environmental stressors are likely to influence the environmental fate and biological availability of heavy metals. Microplastics can adsorb and transport toxic metals, potentially modifying their distribution and bioavailability in marine organisms (Chen et al., 2023; EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Marmara et al., 2023; Osman et al., 2023; Pazi et al., 2017; Xiong et al., 2024). Climate change may alter seawater temperature, salinity, and circulation, thereby influencing contaminant cycling and exposure pathways. At the same time, increasing seafood consumption may contribute to changing patterns of dietary exposure among different population groups in Türkiye (Chen et al., 2023; EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Köker et al., 2021; Marmara et al., 2023; Osman et al., 2023; Pazi et al., 2017; Xiong et al., 2024). Together, these factors may influence future contamination patterns and should be considered in monitoring and risk assessment programs. The overall conceptual framework of heavy metal contamination, bioaccumulation, trophic transfer, human health risk assessment, and environmental management addressed in this review is summarized in Fig. 1.

Figure 1. Schematic overview of the pathways linking anthropogenic activities, heavy metal contamination, bioaccumulation, trophic transfer, seafood safety, and human health in Turkish marine ecosystems.

2. Materials and Methods

2.1. Literature Search Strategy

The search covered studies published between January 2003 and March 2025 and was conducted using the Web of Science, Scopus, and Google Scholar databases. Additional relevant publications were identified through manual screening of reference lists from selected articles.

The search strategy combined keywords related to heavy metal contamination, marine fish, and Turkish marine environments. The following search terms and their combinations were used: heavy metals, trace elements, fish, marine, ("Turkey" OR "Türkiye"), Black Sea, Sea of Marmara, Aegean Sea, Mediterranean Sea, bioaccumulation, human health risk, health risk assessment, mercury, cadmium, lead, and metal contamination.

Only peer-reviewed journal articles published in English were considered for inclusion.

2.2. Study Selection Process

The literature search identified publications from the Web of Science, Scopus, and Google Scholar databases. After removing duplicate records, the remaining articles were screened based on their titles and abstracts. Full-text evaluation was subsequently performed according to the predefined eligibility criteria. Studies focusing exclusively on freshwater fish, aquaculture experiments, laboratory exposure studies, sediments, seawater, shellfish, or other marine organisms without marine fish data from Turkish seas were excluded. Following the screening and eligibility assessment, 59 peer-reviewed studies were included in the final qualitative synthesis. The overall study selection process is summarized in Fig. 2.

Figure 2. PRISMA flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies used in this systematic review of heavy metal contamination in marine fish from Turkish seas.

2.3. Eligibility Criteria and Data Extraction

Studies were included if they met the following criteria:

- investigated marine fish species collected from one or more Turkish seas;
- reported quantitative concentrations of one or more heavy metals or trace elements;
- analyzed edible muscle tissue or provided sufficient information for comparison with edible tissues;
- presented original analytical data obtained from field samples; and
- were published in peer-reviewed scientific journals.

Studies focusing exclusively on freshwater fish, aquaculture experiments, laboratory exposure studies, sediments, seawater, shellfish, or other marine organisms without fish data were excluded.

For each eligible publication, the following information was extracted where available:

- sampling region;
- fish species;
- sampling year;
- analyzed tissue;
- analytical method;
- investigated metals;
- reported metal concentrations; and
- human health risk assessment indices.

2.4. Quality Assessment

To evaluate the reliability and comparability of the reviewed studies, a qualitative methodological assessment was performed. Each study was evaluated according to several methodological criteria relevant to trace element analysis in marine fish, including:

- adequacy of sampling design and description of sampling locations;
- identification of fish species and analyzed tissue;
- use of validated analytical techniques (e.g., FAAS, GFAAS, ICP–OES, ICP–MS);
- implementation of quality assurance and quality control (QA/QC) procedures, including certified reference materials (CRMs), procedural blanks, duplicate analyses, recovery tests, and calibration verification;
- reporting of detection limits (LOD/LOQ) where available;
- presentation of quantitative concentration data using clearly defined reporting units; and
- description of human health risk assessment methodology, where applicable.

Because of the substantial methodological heterogeneity among studies, no formal numerical quality scoring system or risk-of-bias assessment was applied. Instead, methodological strengths and limitations were considered qualitatively during data synthesis and interpretation.

2.5. Data Harmonization

Considerable methodological differences were observed among the reviewed studies, particularly regarding analytical procedures, reporting units, and biological tissues. To improve comparability, reported metal concentrations were evaluated on a wet-weight basis whenever sufficient information was available for conversion (Kayhan et al., 2017; Dalman et al., 2006; Genç, 2021).

Because muscle tissue represents the edible portion most frequently consumed by humans, the present review primarily focused on metal concentrations reported in muscle tissue. The principal contaminants evaluated included mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), iron (Fe), and manganese (Mn).

2.6. Analytical Techniques

The reviewed studies employed a variety of analytical techniques for metal determination. The most frequently used methods included flame atomic absorption spectrometry (FAAS), graphite furnace atomic absorption spectrometry (GFAAS), inductively coupled plasma–optical emission spectrometry (ICP–OES), and inductively coupled plasma–mass spectrometry (ICP–MS) (Bat and Özkan, 2019; Copat et al., 2018; Genç, 2021; Korkmaz et al., 2019).

Most studies also reported quality assurance and quality control (QA/QC) procedures, including the use of certified reference materials, procedural blanks, duplicate analyses, calibration verification, and recovery tests to ensure analytical accuracy and precision (Kayhan et al., 2017; Bat and Özkan, 2019; Güngör and Kara, 2018).

2.7. Human Health Risk Assessment

Potential human health risks associated with dietary exposure to heavy metals were evaluated based on the health risk assessment approaches reported in the reviewed studies. Particular emphasis was placed on Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Hazard Index (HI), and, where available, carcinogenic risk indicators.

These indices were calculated in the original studies using reported metal concentrations in edible fish tissues together with assumptions regarding average fish consumption rates and body weight. Risk characterization was generally based on oral reference doses (RfDs), tolerable daily or weekly intake values, and internationally accepted guideline values established by the United States Environmental Protection Agency (USEPA), the European Food Safety Authority (EFSA), the Joint FAO/WHO Expert Committee on Food Additives (JECFA), and the Codex Alimentarius Commission (Codex Alimentarius Commission, 2016; EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Güngör and Kara, 2018; Means, 1989).

Because this study is a literature review, no additional exposure calculations or statistical analyses were performed. The reported risk indices were synthesized qualitatively to compare contamination patterns and potential health risks among different Turkish marine regions.

3. Results and Discussion

3.1. Regional Distribution Patterns of Heavy Metals in Marine Fish

The reviewed literature demonstrates considerable spatial variability in heavy metal contamination among the four Turkish marine basins. These regional differences are primarily associated with variations in industrialization, urbanization, riverine inputs, hydrodynamic conditions, sediment characteristics, and food-web structure (Tüzen, 2003; Yabanli and Tay, 2021). Table 1 summarizes the principal regional characteristics identified from the reviewed studies. Although direct comparisons among studies are constrained by methodological differences, the available evidence reveals several consistent regional contamination patterns.

Table 1
Regional characteristics of heavy metal contamination in marine fish from Turkish seas.

Marine region	Predominant metal concern	Major environmental drivers	Representative fish species
Sea of Marmara	Pb, Cd	Industrialization, municipal wastewater, maritime traffic, restricted water exchange	<i>Trachurus mediterraneus</i> , <i>Merlangius merlangus</i>
Black Sea	Pb, Cd, Zn	Riverine inputs, coastal urbanization, sediment resuspension	<i>Mullus barbatus</i> , <i>Merlangius merlangus</i>
Aegean Sea	Hg	Biomagnification, oligotrophic food webs, trophic transfer	<i>Merluccius merluccius</i> , <i>Sarda sarda</i>
Mediterranean Sea	Hg	Predatory fish, coastal development, aquaculture, tourism	<i>Scorpaena porcus</i> , <i>Merluccius merluccius</i>

3.1.1. Sea of Marmara

The Sea of Marmara has been the most intensively investigated marine basin in Türkiye with respect to heavy metal contamination in fish. Most reviewed studies reported comparatively higher concentrations of lead (Pb) and cadmium (Cd) than those observed in the other Turkish seas (Findık and Çiçek, 2011; Kayhan et al., 2017; Küpeli et al., 2014; Topcuoglu et al., 2004; Türkmen et al., 2009). The elevated concentrations are generally attributed to intensive industrial activities, dense urbanization, municipal wastewater discharges, shipping traffic, and restricted water circulation within this semi-enclosed basin (Findık and Çiçek, 2011; Kayhan et al., 2017; Küpeli et al., 2014).

In addition to continuous anthropogenic inputs, contaminated bottom sediments represent an important secondary source of pollution. Metals accumulated in sediments may be remobilized by dredging, storms, bottom trawling, or natural sediment disturbance, thereby increasing their bioavailability to benthic organisms and demersal fish species (Wang and Rainbow, 2008; Yabanli and Tay, 2021). Consequently, fish inhabiting coastal industrial areas of the Sea of Marmara frequently exhibit relatively higher concentrations of Pb and Cd than those collected from less impacted regions (Dökmeci et al., 2019; Erkan et al., 2020; Küpeli et al., 2014; Türkmen et al., 2009). These findings support the characterization of the Sea of Marmara as the Turkish marine basin most affected by anthropogenic heavy metal inputs (Table 1).

3.1.2. Black Sea

The reviewed studies indicate that heavy metal contamination in the Black Sea is strongly influenced by riverine transport from one of Europe's largest international drainage basins. Rivers deliver nutrients, suspended particles, organic matter, and contaminants originating from numerous upstream industrial and agricultural areas. In addition, land-based pollution sources along the Turkish Black Sea coast have

been identified as important contributors to coastal environmental contamination (Bat et al., 2009; Bat et al., 2018; Bosch et al., 2016; Çulha et al., 2016; Findik and Çiçek, 2011; Kara et al., 2020; Karslı, 2021; Mendil et al., 2010; Mol et al., 2017; Türkmen and Dura, 2016; Şirin, 2020; Şirin et al., 2024; Şirin et al., 2025).

Although the majority of investigated fish species contained metal concentrations below internationally accepted food safety limits, several studies identified localized contamination hotspots near river mouths, ports, and densely populated coastal areas (Alkan et al., 2016; Bat et al., 2018; Kara et al., 2020; Mendil et al., 2010; Türkmen and Dura, 2016). Sediment-associated metals appear to play an important role in determining exposure levels in benthic fish species. Accordingly, red mullet (*Mullus barbatus*) and whiting (*Merlangius merlangus*) are among the species most frequently used as bioindicators of metal contamination in the Turkish Black Sea because of their close association with bottom sediments and benthic prey (Bozcaarmutlu et al., 2020; Çulha et al., 2016; Kara et al., 2020; Türkmen and Dura, 2016; Vetsis et al., 2021). Recent studies from the Black Sea also indicated that metal concentrations in commercially important fish species generally remained below international food safety limits, although continued monitoring remains necessary because of ongoing anthropogenic pressures and seafood consumption concerns (Öztürk, 2022). The predominant contamination characteristics of the Black Sea are summarized in Table 1.

3.1.3. Aegean Sea

Compared with the Sea of Marmara, the Aegean Sea generally exhibited lower concentrations of lead and cadmium in marine fish. However, several reviewed studies reported relatively higher mercury concentrations in predatory fish occupying higher trophic levels (Dalman et al., 2006; Artar et al., 2024; Genç, 2021; Kaya and Türkoğlu, 2017; Türkmen et al., 2009; Tas et al., 2011). This pattern is consistent with the ecological characteristics of the oligotrophic Aegean ecosystem, where longer and more complex food webs facilitate the biomagnification of methylmercury (Burger and Gochfeld, 2005; Lavoie et al., 2013).

Predatory species generally accumulated higher mercury concentrations than pelagic planktivorous species, reflecting differences in feeding ecology and trophic position rather than direct environmental exposure alone (Artar et al., 2024; Genç, 2021; Kaya and Türkoğlu, 2017). Similar concentration patterns have also been reported for several fish species collected from the Aegean region (Tekin-Özan, 2014).

3.1.4. Mediterranean Sea

The Mediterranean Sea exhibits contamination patterns broadly similar to those observed in the Aegean Sea. Mercury was identified as the metal of greatest concern in predatory marine fish because of its high bioaccumulation and biomagnification potential (Korkmaz et al., 2019; Ustaoglu and Yüksel, 2024). Local anthropogenic activities, including coastal urbanization, agricultural runoff, aquaculture, tourism, and maritime transport, may further contribute to localized contamination in several coastal regions, particularly Antalya and İskenderun Bays (Korkmaz et al., 2019; Yabanli and Tay, 2021).

Despite these localized pressures, most reviewed studies reported metal concentrations below international regulatory limits for commercially important fish species. Nevertheless, continued monitoring remains essential because the Mediterranean supports economically valuable fisheries and receives increasing anthropogenic pressures associated with coastal development and climate-related environmental changes (Korkmaz et al., 2019; Ustaoglu and Yüksel, 2024).

Taken together, the reviewed studies indicate that regional pollution sources, sediment characteristics, hydrodynamic conditions, and species ecology jointly influence heavy metal accumulation in marine fish from Turkish seas. The regional similarities and differences identified in the reviewed studies are summarized in Table 1.

3.2. Bioaccumulation and Trophic Transfer

Heavy metal accumulation in marine fish is a dynamic process governed by multiple biological, ecological, and environmental factors. Evidence suggests that metals may enter fish through direct uptake from the surrounding water via the gills, ingestion of contaminated food, and incidental consumption of sediment particles, with the relative importance of each pathway depending on both the physicochemical properties of individual metals and species-specific ecological characteristics (Ali and Khan, 2019; Burger and Gochfeld, 2005; Lavoie et al., 2013). Once absorbed, metals are distributed among different tissues according to their chemical behavior, metabolic activity, and affinity for biological molecules. Consequently, accumulation patterns differ substantially among fish species occupying different habitats and trophic levels.

Although environmental contamination constitutes the primary source of metal exposure, the reviewed evidence suggests that trophic position, feeding behavior, habitat preference, age, body size, and longevity collectively determine the magnitude of metal accumulation in marine fish (Ali and Khan, 2019; Burger and Gochfeld, 2005; Lavoie et al., 2013). Predatory species generally accumulate higher concentrations of biomagnifying contaminants than lower trophic-level species because dietary exposure becomes increasingly important at successive trophic levels. Table 2 presents typical bioaccumulation characteristics of the investigated metals. The overall relationships among environmental contamination, bioaccumulation, trophic transfer, and human exposure are presented conceptually in Fig. 1.

Table 2

General characteristics of bioaccumulation and trophic transfer of major metals reported in marine fish from Turkish seas.

Metal	Major uptake pathway	Bioaccumulation potential	Biomagnification potential	Primary controlling factors
Mercury (Hg)	Dietary exposure (methylmercury)	Very high	Very high	Trophic level, longevity, feeding ecology
Cadmium (Cd)	Sediment and diet	Moderate	Low	Sediment contamination, benthic habitat
Lead (Pb)	Sediment, suspended particles	Moderate	Low	Coastal pollution, industrial inputs
Copper (Cu)	Water and diet	Moderate	Negligible	Physiological regulation
Zinc (Zn)	Water and diet	Moderate	Negligible	Homeostatic control
Iron (Fe)	Water and diet	Moderate	Negligible	Physiological demand
Chromium (Cr)	Water, sediment, diet	Low–Moderate	Low	Environmental availability
Nickel (Ni)	Water and diet	Low	Low	Environmental exposure
Manganese (Mn)	Water and diet	Moderate	Negligible	Physiological regulation
Arsenic (As)	Diet	Moderate	Variable	Chemical speciation, feeding ecology

3.2.1. Mercury Biomagnification

Among the metals evaluated, mercury (Hg) demonstrates the clearest evidence of trophic biomagnification. Most reviewed studies reported progressively increasing mercury concentrations from lower trophic organisms to large predatory fish (Burger and Gochfeld, 2005; Lavoie et al., 2013). Unlike many other metals, mercury is readily transformed into methylmercury by aquatic microorganisms (Burger and Gochfeld, 2005; Lavoie et al., 2013). This organic form is highly bioavailable, efficiently assimilated through dietary exposure, and only slowly eliminated from fish tissues. As a result, methylmercury accumulates throughout the food web and reaches its highest concentrations in long-lived predatory species (Burger and Gochfeld, 2005; Lavoie et al., 2013).

Studies conducted in Turkish marine waters consistently reported elevated mercury concentrations in predatory species such as Atlantic bonito (*Sarda sarda*), European hake (*Merluccius merluccius*), bluefish (*Pomatomus saltatrix*), and scorpionfish (*Scorpaena porcus*) compared with pelagic species including anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*) (Artar et al., 2024; Burger and Gochfeld, 2005; Çulha et al., 2016; Kaya and Türkoğlu, 2017; Mol et al., 2017; Vetsis et al., 2021). Although the majority of reported concentrations remained below international maximum permissible limits, these findings confirm that trophic transfer is a major determinant of mercury accumulation in commercially harvested fish.

3.2.2. Cadmium and Lead

The accumulation patterns of cadmium (Cd) and lead (Pb) differ considerably from those of mercury. Published investigations indicate that these metals exhibit relatively limited trophic biomagnification and are more strongly influenced by environmental exposure, particularly sediment contamination and benthic feeding behavior (Ali and Khan, 2019; Bat and Özkan, 2019; Dalman et al., 2006; Güngör and Kara, 2018). Consequently, demersal species living in close association with bottom sediments frequently contain higher Cd and Pb concentrations than pelagic fish occupying the water column.

In the Sea of Marmara and several Black Sea coastal areas, elevated Cd and Pb concentrations have frequently been associated with industrial discharges, riverine transport, urban wastewater, and historical sediment contamination (Fındık and Çiçek, 2011; Kayhan et al., 2017; Küpeli et al., 2014; Türkmen et al., 2009). Fish species inhabiting these environments therefore provide valuable information for assessing localized anthropogenic pollution.

3.2.3. Essential Trace Elements

Unlike mercury, cadmium, and lead, several trace elements including copper (Cu), zinc (Zn), iron (Fe), and manganese (Mn) are essential micronutrients required for normal physiological functions. The reviewed studies generally reported that concentrations of these elements are regulated through homeostatic mechanisms, resulting in comparatively lower variability among fish species (Ali and Khan, 2019; Genç, 2021; Kayhan et al., 2017). Nevertheless, excessive environmental exposure may disrupt physiological regulation and lead to elevated tissue concentrations, particularly in contaminated coastal environments.

Because essential elements are actively regulated by fish metabolism, their tissue concentrations do not necessarily increase with trophic level. Instead, accumulation reflects a combination of environmental availability, species-specific metabolic requirements, dietary composition, and habitat characteristics (Ali and Khan, 2019; Burger and Gochfeld, 2005).

3.2.4. Species-Specific Bioaccumulation Patterns

Species ecology represents one of the principal determinants of heavy metal accumulation. Benthic fish species such as red mullet (*Mullus barbatus*) and whiting (*Merlangius merlangus*) frequently accumulate relatively higher concentrations of sediment-associated metals because of their close association with

contaminated bottom habitats and benthic prey (Bozcaarmutlu et al., 2020; Çulha et al., 2016; Dökmeci et al., 2019; Kara et al., 2020; Öztürk, 2022; Türkmen and Dura, 2016). In contrast, pelagic species including anchovy and sardine generally exhibit lower concentrations of sediment-associated metals but remain important contributors to dietary metal exposure because they are consumed in large quantities by the Turkish population (Bat et al., 2024; Kontas et al., 2022; Korkmaz et al., 2019; Mendil et al., 2010).

Predatory species occupying upper trophic levels generally accumulate higher mercury concentrations owing to progressive biomagnification, whereas benthic species tend to reflect local environmental contamination associated with sediments. These complementary ecological characteristics make marine fish valuable bioindicators for monitoring both regional pollution and contaminant transfer through marine food webs.

Taken together, the reviewed studies demonstrate that heavy metal accumulation in marine fish is shaped by both environmental conditions and species ecology. Differences in habitat use, feeding behavior, trophic position, and longevity influence metal burdens and should therefore be considered when evaluating seafood safety and ecological risk.

3.3. Compliance with International Food Safety Standards

The safety of marine fish for human consumption is commonly evaluated by comparing measured heavy metal concentrations with maximum permissible limits established by international regulatory organizations. The reviewed studies primarily compared their analytical results with guideline values published by the European Commission (EC), the Codex Alimentarius Commission, the European Food Safety Authority (EFSA), the Joint FAO/WHO Expert Committee on Food Additives (JECFA), and the United States Environmental Protection Agency (USEPA) (Codex Alimentarius Commission, 2019; EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Güngör and Kara, 2018; Means, 1989). To facilitate interpretation of the reviewed findings, the principal international maximum permissible limits adopted for heavy metals in fish are summarized in Table 3.

Table 3

International guideline values commonly used for evaluating heavy metal concentrations in marine fish.

Metal	Guideline value*	Regulatory organization	Primary health concern
Mercury (Hg)	0.5 mg kg ⁻¹ (most species); 1.0 mg kg ⁻¹ (predatory species)	European Commission (EC); Codex Alimentarius	Neurotoxicity; fetal development
Cadmium (Cd)	0.05 mg kg ⁻¹	European Commission (EC)	Kidney toxicity; skeletal effects
Lead (Pb)	0.30 mg kg ⁻¹	European Commission (EC)	Neurotoxicity; cardiovascular effects
Arsenic (As)**	No universal limit for total As	EFSA; JECFA	Depends on inorganic arsenic fraction
Copper (Cu)	Not generally regulated	National/Regional guidance	Essential element; toxicity at high exposure
Zinc (Zn)	Not generally regulated	National/Regional guidance	Essential element; excessive intake may cause adverse effects
Iron (Fe)	Not generally regulated	Nutritional reference values	Essential element
Chromium (Cr)	No internationally harmonized limit	Various authorities	Speciation-dependent toxicity
Nickel (Ni)	No internationally harmonized limit	Various authorities	Allergic reactions; chronic exposure
Manganese (Mn)	Not generally regulated	Nutritional reference values	Essential element
*Guideline values shown represent those most frequently used by the reviewed studies and may vary according to fish species, legislation, and regulatory updates.			
**For arsenic, human health risk depends primarily on the concentration of inorganic arsenic rather than total arsenic.			

Overall, the available evidence indicates that heavy metal concentrations in fish species from Turkish waters generally remained below current international regulatory limits (Alkan et al., 2016; Artar et al., 2024; Bat and Özkan, 2019; Copat et al., 2018; Dalman et al., 2006; Korkmaz et al., 2019; Lavoie et al., 2013; Mendil et al., 2010; Mol et al., 2017; Türkmen et al., 2009; Wang and Rainbow, 2008). However, localized contamination hotspots associated with industrial activities, urbanization, and coastal pollution emphasize the need for continuous ecosystem-based monitoring to safeguard seafood quality, marine ecosystem health, and human well-being.

Nevertheless, occasional exceedances were reported for particular metals, fish species, and sampling locations, especially in areas exposed to intensive industrial activities or localized anthropogenic pollution. These findings emphasize that contamination is not uniformly distributed among Turkish

marine ecosystems and that regional environmental conditions play an important role in determining seafood quality.

Mercury received particular attention because of its high toxicity and its ability to biomagnify through marine food webs. Although most reviewed studies reported mercury concentrations below the regulatory limits established for fishery products, relatively higher concentrations were consistently observed in large predatory species occupying upper trophic levels (Artar et al., 2024; Burger and Gochfeld, 2005; Çulha et al., 2016; Kaya and Türkoğlu, 2017; Lavoie et al., 2013; Mol et al., 2017; Vetsis et al., 2021). Consequently, regular monitoring of mercury remains an important component of seafood safety programmes, particularly for species that constitute a significant proportion of commercial landings and human consumption.

Cadmium and lead were also frequently evaluated because both elements originate primarily from anthropogenic activities and may accumulate in coastal environments affected by industrial discharges, municipal wastewater, shipping activities, and contaminated sediments (Dalman et al., 2006; Findık and Çiçek, 2011; Kayhan et al., 2017; Küpeli et al., 2014; Türkmen et al., 2009). The reviewed evidence indicates that concentrations of these metals generally complied with international regulatory limits, although localized increases were occasionally reported in fish collected from the Sea of Marmara and selected Black Sea coastal areas (Dalman et al., 2006; Findık and Çiçek, 2011; Kayhan et al., 2017; Küpeli et al., 2014; Türkmen et al., 2009; Bat and Özkan, 2019). These observations highlight the importance of site-specific environmental monitoring rather than relying exclusively on nationwide average values.

Essential trace elements such as copper, zinc, iron, and manganese were reported in nearly all reviewed studies. Because these elements are physiologically required for normal biological functions, no universal maximum permissible limits have been established for several of them in fishery products. Nevertheless, unusually elevated concentrations may indicate environmental contamination or excessive anthropogenic inputs and therefore remain valuable indicators for ecological monitoring (Ali and Khan, 2019; Genç, 2021; Kayhan et al., 2017).

Direct comparisons should be made cautiously. Fish species, sampling season, specimen size, analytical methods, reporting units, and tissue selection all affect results (Ali and Khan, 2019; Ateş et al., 2015; Güngör and Kara, 2018; Kayhan et al., 2017). Still, the evidence consistently shows that commercially important fish from Turkish waters generally meet international safety standards. Localized hotspots, however, need continued surveillance.

The reviewed literature therefore supports the continuation of long-term monitoring programmes that integrate environmental contamination data with food safety assessments. Such programmes are essential for the early identification of emerging contamination trends, evaluation of temporal changes in metal concentrations, and protection of both marine ecosystem health and seafood consumers.

3.4. Human Health Risk Assessment

The presence of heavy metals in marine fish does not necessarily indicate an immediate risk to human health. The actual health risk depends on several factors, including the concentration of metals in edible tissues, fish consumption rate, body weight, exposure frequency, and the toxicological characteristics of individual elements. Consequently, the reviewed studies increasingly incorporated quantitative human health risk assessment approaches to evaluate the potential effects of dietary exposure to heavy metals through fish consumption (Codex Alimentarius Commission, 2019; EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Güngör and Kara, 2018; USEPA, 1989). The general human health risk assessment pathway adopted in the reviewed studies is incorporated within the conceptual framework shown in Fig. 1.

The reviewed studies primarily assessed dietary exposure using Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI). These indices provide complementary information regarding potential non-carcinogenic health risks associated with seafood consumption. A summary of these risk indicators and their interpretation is presented in Table 4.

Table 4
Human health risk assessment indices commonly applied in the reviewed studies.

Risk index	Purpose	General interpretation	Regulatory basis
Estimated Daily Intake (EDI)	Estimates daily dietary exposure	Compared with tolerable daily/weekly intake values	EFSA, JECFA
Target Hazard Quotient (THQ)	Assesses non-carcinogenic risk for individual metals	THQ < 1: negligible risk; THQ ≥ 1: potential concern	USEPA
Hazard Index (HI)	Evaluates cumulative non-carcinogenic risk	HI < 1: acceptable combined exposure; HI ≥ 1: potential cumulative risk	USEPA
Carcinogenic Risk (CR)*	Estimates lifetime cancer risk for carcinogenic elements	Acceptable risk generally between 10 ⁻⁶ and 10 ⁻⁴	USEPA
*Carcinogenic Risk (CR) was reported in only a limited number of the reviewed studies because carcinogenic slope factors are available for relatively few heavy metals.			

3.4.1. Estimated Daily Intake (EDI)

Estimated Daily Intake (EDI) represents the amount of a contaminant ingested daily through fish consumption relative to body weight. The reviewed studies calculated EDI using measured metal concentrations in edible muscle tissue together with assumptions regarding average fish consumption rates and body weight (Codex Alimentarius Commission, 2019; EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Güngör and Kara, 2018). Although calculation parameters differed slightly among studies, EDI remains one of the most widely applied indicators for evaluating dietary exposure.

Most reviewed studies reported EDI values below the tolerable intake levels established by international organizations for mercury, cadmium, lead, and other investigated metals (Alkan et al., 2016; Artar et al., 2024; Bat and Özkan, 2019; Copat et al., 2018; Dalman et al., 2006; Korkmaz et al., 2019; Lavoie et al., 2013; Mendil et al., 2010; Mol et al., 2017; Türkmen et al., 2009). However, dietary exposure may increase substantially among individuals with frequent seafood consumption, particularly in coastal communities where fish constitutes a regular component of the daily diet.

3.4.2. Target Hazard Quotient (THQ)

Target Hazard Quotient (THQ) is widely used to estimate the probability of adverse non-carcinogenic health effects resulting from long-term dietary exposure. According to USEPA methodology, THQ values below one generally indicate that adverse health effects are unlikely during a lifetime of exposure, whereas values exceeding one may suggest a potential health concern (Means, 1989).

The reviewed literature consistently reported THQ values below one for most seafood species collected from Turkish waters (Bat and Özkan, 2019; Bat et al., 2024; Copat et al., 2018; Güngör and Kara, 2018; Korkmaz et al., 2019; Means, 1989). These findings indicate that average fish consumption is generally not expected to pose significant non-carcinogenic health risks to the general adult population. Nevertheless, several studies emphasized that THQ values may increase under scenarios involving high seafood consumption or elevated contamination in specific fish species.

Mercury frequently contributed the largest proportion of total THQ because of its relatively low oral reference dose and high bioaccumulation potential. In contrast, cadmium and lead generally produced lower individual THQ values despite their recognized toxicological significance (Burger and Gochfeld, 2005; Lavoie et al., 2013; Güngör and Kara, 2018).

3.4.3. Hazard Index (HI)

Because consumers are simultaneously exposed to multiple heavy metals through seafood consumption, several reviewed studies calculated the Hazard Index (HI), which represents the sum of individual THQ values. HI provides an integrated assessment of cumulative non-carcinogenic risk associated with combined exposure to multiple contaminants.

Most reviewed studies reported HI values below one, suggesting that cumulative exposure through the consumption of fish species from Turkish waters is generally within acceptable safety limits for the average consumer (Bat and Özkan, 2019; Bat et al., 2024; Copat et al., 2018; Güngör and Kara, 2018; Korkmaz et al., 2019). However, localized contamination, frequent fish consumption, and the preferential consumption of large predatory fish may increase cumulative exposure in specific population groups.

3.4.4. Sensitive Population Groups

Although the reviewed evidence generally indicates low non-carcinogenic risk for the general population, several studies emphasized that risk assessments should also consider vulnerable groups such as children, pregnant women, nursing mothers, and individuals with high seafood consumption rates

(Codex Alimentarius Commission, 2019; EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Means, 1989; Bat et al., 2024). These groups may experience proportionally greater dietary exposure because of lower body weight, increased physiological sensitivity, or higher nutritional dependence on seafood.

Particular attention has been given to methylmercury because of its ability to cross both the placental and blood–brain barriers, potentially affecting fetal neurological development during pregnancy (Burger and Gochfeld, 2005; Lavoie et al., 2013; Means, 1989). Consequently, international health authorities recommend balancing the nutritional benefits of fish consumption with the selection of species that contain relatively low mercury concentrations.

Children and pregnant women are particularly susceptible to the neurotoxic effects of methylmercury (Bat et al., 2024; Demirtaş et al., 2024). Consumption limits for pregnant women and children consuming predatory fish from the Aegean Sea have been recommended (Kaya and Türkoğlu, 2017). Cumulative health risks from multiple metals in Marmara fish have been highlighted (Güngör and Kara, 2018), and risk levels for toxic metals have been shown to vary by age group in consumers of Marmara Sea fish (Erkan et al., 2020). While most fish in Turkey are safe, continuous monitoring is essential, especially for vulnerable groups (Köker et al., 2021).

3.4.5. Overall Health Risk Assessment

The available evidence suggests that marine fish harvested from Turkish waters are generally safe for consumption under normal dietary habits. However, contamination levels may vary among species, marine regions, and local environmental conditions. Predatory fish occupying higher trophic levels tend to accumulate greater concentrations of mercury, whereas benthic species more often reflect localized contamination associated with sediments and coastal pollution sources.

These observations underline the importance of continuous monitoring programmes that combine environmental measurements with food safety assessments. Regular updates of dietary exposure estimates based on current seafood consumption patterns would also contribute to more effective risk communication and evidence-based recommendations for consumers.

3.5. Emerging Environmental Drivers

Although industrialization, urbanization, and riverine inputs remain the principal sources of heavy metal contamination in Turkish marine ecosystems, several emerging environmental drivers are increasingly recognized as factors that may influence the transport, bioavailability, and ecological behavior of heavy metals (Chen et al., 2023; Marmara et al., 2023; Osman et al., 2023; Pazi et al., 2017; Xiong et al., 2024). Among these, microplastic pollution and climate change have received growing scientific attention because of their potential to modify contaminant pathways and exposure dynamics.

Microplastics are now widely distributed throughout marine ecosystems and have been detected in seawater, sediments, and numerous marine organisms. Owing to their large surface area and

physicochemical properties, microplastics can adsorb and transport toxic metals, potentially modifying their distribution and bioavailability in marine organisms (Chen et al., 2023; EFSA, 2012; Marmara et al., 2023; Osman et al., 2023; Pazi et al., 2017; Xiong et al., 2024). Consequently, they may function as vectors that transport metals across different environmental compartments and potentially increase contaminant availability to marine organisms through ingestion.

The reviewed literature suggests that interactions between microplastics and heavy metals are complex and depend on polymer composition, particle size, environmental conditions, and metal speciation (Chen et al., 2023; Marmara et al., 2023; Osman et al., 2023; Pazi et al., 2017; Xiong et al., 2024). Although relatively few studies have directly investigated these interactions in Turkish marine ecosystems, the available evidence indicates that microplastics may modify metal uptake pathways, particularly in lower trophic organisms that are readily consumed by fish. These processes could ultimately influence trophic transfer and dietary exposure in marine food webs.

Climate change represents another important factor that may alter heavy metal cycling within marine ecosystems. Rising seawater temperatures, changes in salinity, altered precipitation patterns, ocean circulation, and increasing frequency of extreme weather events may influence metal mobility, sediment resuspension, and biogeochemical cycling (EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Marmara et al., 2023; Xiong et al., 2024). Such environmental changes have the potential to modify contaminant bioavailability and accumulation in aquatic organisms, although considerable uncertainty remains regarding the magnitude of these effects under future climate scenarios.

In addition to environmental changes, increasing seafood consumption may influence population-level dietary exposure to heavy metals. Fish remains an important component of a healthy diet because of its high nutritional value; however, consumption patterns vary considerably among regions and population groups (Köker et al., 2021). Therefore, future health risk assessments should integrate both contaminant concentrations and evolving seafood consumption habits to provide more realistic estimates of long-term exposure.

Future assessments of heavy metal contamination should consider not only traditional pollution sources but also emerging environmental pressures such as microplastic pollution and climate change. Instead, future monitoring programmes should consider the combined influence of conventional contaminant inputs, microplastic pollution, climate-related environmental changes, and shifting patterns of seafood consumption.

3.6. Methodological Heterogeneity and Knowledge Gaps

A major challenge encountered during this review was the substantial methodological variability among published studies. Although the reviewed studies collectively provide valuable information regarding regional contamination patterns, direct comparison among investigations remains challenging because of variability arising from sampling strategies, analytical methodologies, reporting units, and health risk assessment approaches (Ali and Khan, 2019; Ateş et al., 2015; Güngör and Kara, 2018; Kayhan et al.,

2017). These methodological differences were also considered during the qualitative quality assessment performed in the present review and were taken into account when interpreting regional contamination patterns and health risk assessments.

Sampling protocols differed substantially with respect to sampling location, sampling season, fish species, specimen size, age structure, and the biological tissues selected for analysis. While most studies focused on edible muscle tissue, others additionally analyzed liver, gill, kidney, or gonadal tissues, which naturally accumulate metals at different rates. These differences complicate direct comparison of reported concentrations across studies and may contribute to apparent regional variability.

Analytical methodologies have also evolved considerably over the past two decades. Earlier investigations frequently employed flame atomic absorption spectrometry (FAAS) or graphite furnace atomic absorption spectrometry (GFAAS), whereas more recent studies increasingly utilize inductively coupled plasma–optical emission spectrometry (ICP–OES) and inductively coupled plasma–mass spectrometry (ICP–MS), which generally provide improved analytical sensitivity and lower detection limits (Bat and Özkan, 2019; Copat et al., 2018; Genç, 2021; Korkmaz et al., 2019). Although most reviewed studies implemented appropriate quality assurance and quality control (QA/QC) procedures, differences in analytical performance may still influence reported metal concentrations.

Additional variability arises from the use of different reporting units. Some studies reported concentrations on a wet-weight basis, whereas others presented dry-weight values without providing sufficient information for accurate conversion. Furthermore, considerable variation exists in the fish consumption rates, body weights, oral reference doses, and regulatory guideline values applied during human health risk assessments (Codex Alimentarius Commission, 2019; EFSA Panel on Contaminants in the Food Chain (CONTAM) 2012; Güngör and Kara, 2018; Means, 1989). These methodological inconsistencies limit direct comparison of Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) values among studies.

The reviewed literature also reveals several important knowledge gaps. Long-term monitoring datasets remain limited for many coastal regions, making it difficult to evaluate temporal trends in environmental contamination. In addition, relatively few studies have simultaneously investigated heavy metals, microplastics, and other emerging contaminants within integrated ecosystem-based monitoring frameworks. Information regarding metal speciation, particularly for mercury and arsenic, also remains limited despite its importance for toxicological risk assessment.

Greater harmonization of sampling protocols, analytical methodologies, reporting units, and health risk assessment procedures would improve the comparability of future studies. Expanding monitoring efforts to include temporal trends, trophic-level relationships, contaminant speciation, and emerging environmental stressors may also help clarify the processes governing contaminant accumulation in Turkish marine ecosystems.

The principal methodological limitations identified during this review, together with recommendations for future research, are summarized in Table 5.

Table 5
Major methodological limitations identified in the reviewed studies and recommendations for future research.

Identified limitation	Potential consequence	Recommended future approach
Differences in sampling design	Reduced comparability among studies	Standardized sampling protocols
Different fish species and tissues	Species-dependent variability	Focus on edible muscle tissue and standardized biological descriptors
Wet-weight and dry-weight reporting	Difficulty in data comparison	Report both wet- and dry-weight concentrations
Variable analytical methodologies	Differences in detection limits and precision	Harmonized ICP–MS and QA/QC procedures
Inconsistent health risk assessment assumptions	Limited comparability of EDI, THQ, and HI values	Standardized exposure parameters
Limited long-term monitoring	Insufficient assessment of temporal trends	Continuous national monitoring programmes
Limited information on metal speciation	Uncertainty in toxicological evaluation	Determination of methylmercury and inorganic arsenic
Limited integration of emerging contaminants	Incomplete ecosystem assessment	Integrated monitoring of metals, microplastics, and climate variables

4. Conclusion

This review synthesizes the available evidence on heavy metal contamination in marine fish from the four Turkish seas based on studies published between 2003 and 2025. The findings indicate clear regional differences in contamination patterns that are closely related to pollution sources, hydrodynamic conditions, sediment characteristics, fish ecology, and trophic position. Lead and cadmium were generally more prominent in the Sea of Marmara, whereas mercury represented the primary concern in predatory species because of its tendency to bioaccumulate and biomagnify. Although most reported metal concentrations remained below international regulatory limits, localized contamination hotspots were identified in several coastal areas, emphasizing the need for continued environmental surveillance.

The reviewed studies also demonstrate that heavy metal accumulation cannot be explained solely by environmental contamination levels. Species ecology, feeding behavior, habitat preference, and trophic position strongly influence metal accumulation and should therefore be considered when interpreting monitoring data and evaluating potential risks to seafood safety and public health.

This review also provides a reference point for future studies on marine environmental quality in Türkiye. As industrial development, mining activities, coastal urbanization, and other human pressures continue to evolve, long-term monitoring will be essential for identifying changes in heavy metal contamination and their implications for marine ecosystems and seafood safety. In particular, the increasing number of mining projects and expanding industrial activities in several regions of Türkiye may alter contaminant inputs to aquatic environments over the coming decades. Future investigations using standardized analytical methods and comparable reporting approaches will improve the assessment of temporal trends and support science-based environmental management, seafood safety strategies, and environmental policy decisions.

Declarations

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Ethical Approval

Not applicable. This study is a systematic review based exclusively on previously published literature and did not involve human participants or animals.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Competing Interests

The authors declare that they have no competing interests.

Data Availability Statement

No new primary data were generated in this study. All data analyzed in this systematic review were obtained from previously published studies cited in the article.

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Figures

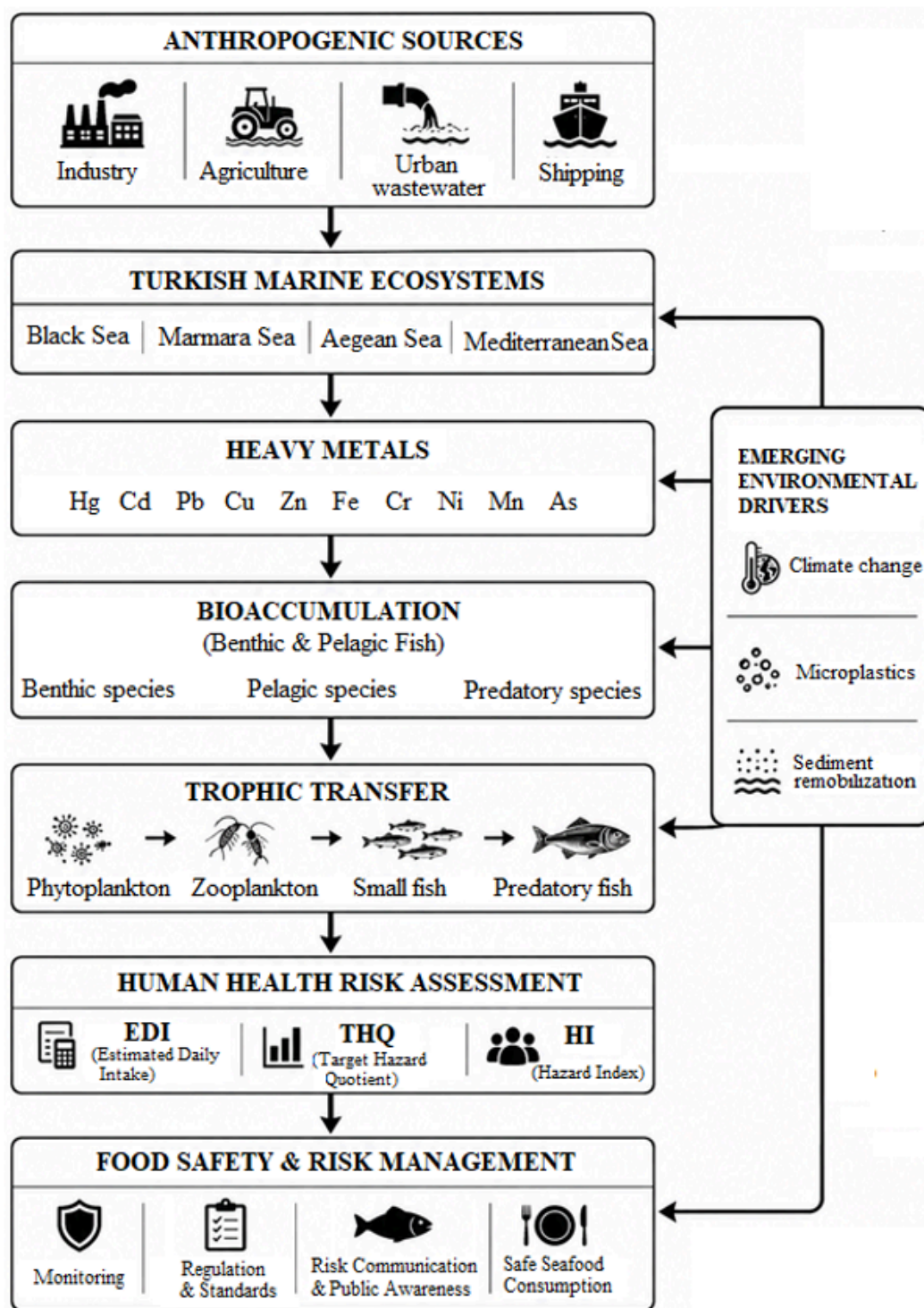


Figure 1

Schematic overview of the pathways linking anthropogenic activities, heavy metal contamination, bioaccumulation, trophic transfer, seafood safety, and human health in Turkish marine ecosystems.

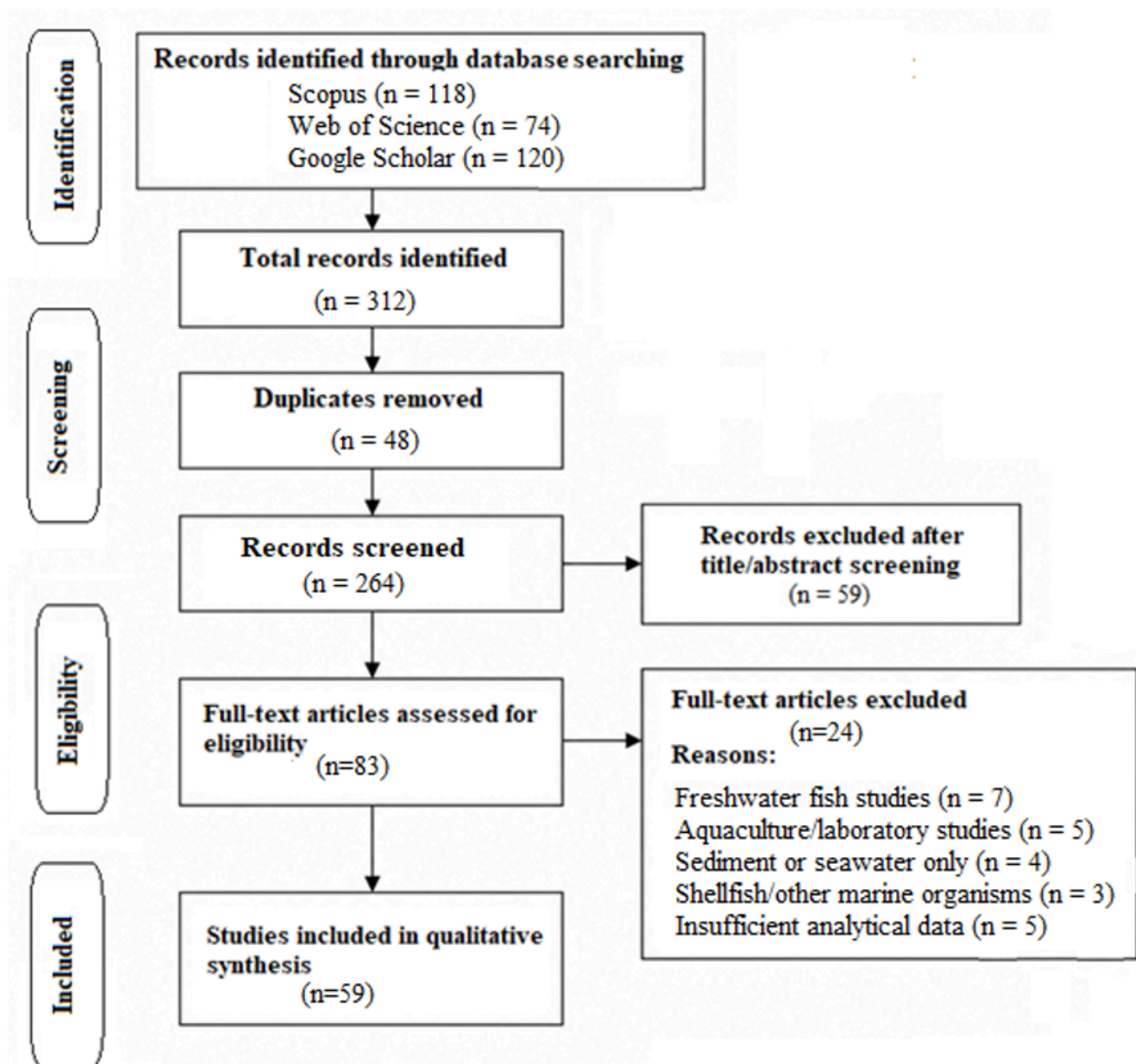


Figure 2

PRISMA flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies used in this systematic review of heavy metal contamination in marine fish from Turkish seas.