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Heavy metal risks in aquatic foods

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ABSTRACT

Aquatic foods provide essential nutrients but can also contain hazardous heavy metals like mercury, cadmium, lead, and arsenic, posing health risks. This study analysed over 138,000 records from the World Health Organization to assess heavy metal levels in aquatic foods, conducting health risk and risk–benefit assessments. Results showed that 97.6 % of aquatic products met safety standards, with mercury at 96.2 % and cadmium at 97.2 % compliance, but species standards varied, and regional compliance differences were observed. Mercury levels are relatively high in fish, while cadmium, lead, and arsenic levels are elevated in molluscs, and cadmium levels are high in cephalopods. Mercury is biomagnified through the food chain, while cadmium, lead, and arsenic exhibit biodilution. Health risk assessment showed that mercury is the primary non-cancer risk, while cadmium, lead, and arsenic are sources of cancer risk. Mercury from aquatic food consumption exceeded the non-cancer risk threshold in 69 countries, and cadmium exceeded cancer risk threshold in 20 countries, while 152 countries remained within acceptable health risk thresholds. Risk-benefit assessment indicated that the health benefits of EPA + DHA intake from aquatic food consumption outweigh the heavy metal-related risks, with net benefit limits higher than safe consumption limits. Current aquatic consumption level is below safe consumption limits, but reducing consumption of high-risk aquatic products can effectively lower health risks. This study provides a global comprehensive evidence base to inform targeted interventions, policies, industry practices, and consumer choices for mitigating risks while promoting sustainable aquatic food consumption as a vital nutritional resource.

1. Introduction

Aquatic foods harvested from freshwater and the sea, diverse beyond simple categorization as "seafood" or "fish," are increasingly recognised as essential sources of protein, long chain omega-3 fatty acids (EPA + DHA), and micronutrients (vitamins and minerals), nourishing nations worldwide (Golden et al., 2021; Hicks et al., 2019; Naylor et al., 2021; Zhang et al., 2022b). However, the presence of bioaccumulative pollutants such as mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As) in aquatic foods poses significant health risks, undermining public health and consumer confidence (FAO/WHO, 2024; Han et al., 2020; Järup, 2003; Stentiford et al., 2022; Yang et al., 2025).

Mercury readily crosses the blood–brain barrier, damaging neuronal cell membranes and mitochondria, causing nervous system injury (Kim et al., 2016). Cadmium destroys renal tubular epithelial cells, disrupts calcium metabolism, leading to kidney damage, osteoporosis, and cancer (Johri et al., 2010). Lead interferes with haemoglobin synthesis, inhibits key enzyme activities, affecting the nervous and blood systems (Collin et al., 2022). Arsenic causes oxidative stress and cellular damage, triggering skin lesions and various cancers (Kapaj et al., 2006). The World Health Organization (WHO) identifies these four heavy metals among its '10 chemicals of major public health concern,' emphasizing the urgent need for monitoring and mitigation strategies for these chemical hazards (WHO, 2020a). The United States Food and Drug

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Administration (FDA)'s 'Closer to Zero' initiative emphasised the need to prioritise reducing the presence of these four metals in foods (FDA, 2021a). The United States Environmental Protection Agency (USEPA)'s fish and shellfish advisory program also emphasizes the need for monitoring of these four metals (USEPA, 2025).

The health risks and toxicity associated with heavy metals are complex and multifaceted, influenced by a confluence of factors such as consumption patterns, dosage, exposure routes, and the nature of the heavy metals involved (Briffa et al., 2020; Tchounwou et al., 2012). This complexity is further compounded in aquatic foods due to the hundreds of species involved and their various environments (Hicks et al., 2019; Zhang et al., 2022b). Heavy metals can accumulate in aquatic foods through various mechanisms, influenced by the organisms' unique biological characteristics, including classification, dietary preferences, and habitats (Blanchfield et al., 2022; Schartup et al., 2019). Additionally, the intake of aquatic foods, which varies widely across different countries and regions regarding volume, composition and preparation (Naylor et al., 2021), introduces further variability in the risks associated with heavy metal intake. Considering these complexities, policymakers and consumers need precise and accurate information about heavy metal contaminants to make informed decisions that balance the nutritional benefits and potential health risks of consuming aquatic foods (Budnik and Casteleyn, 2019; FAO/WHO, 2024).

There is a significant data gap in food safety concerning diets, nutrition, and health, which requires more adequate indicators and data (Schneider et al., 2023). While the nutritional advantages of consuming aquatic foods have been extensively analysed both globally and at country-specific levels (Golden et al., 2021; Hicks et al., 2019; Naylor et al., 2021), research examining the potential drawbacks remains sparse. Many previous investigations and existing dietary guidelines have focused primarily on the mercury hazards in aquatic foods, neglecting to assess these risks relative to other heavy metals to establish their comparative significance (Cai et al., 2025; Cao et al., 2023; Chen et al., 2025; FAO/WHO, 2024; Watanabe et al., 2021; Xiang et al., 2024). Existing research on heavy metal contamination in aquatic food is narrow in both geographical and taxonomic scope, making it impossible to determine whether taxonomic or geographical differences have a greater impact, and failing to capture the global scope and complexity of this issue (Djedjibegovic et al., 2020; Herceg Romanić et al., 2021; Traven et al., 2023; Watanabe et al., 2021). Some studies have noted variations in heavy metal concentrations across species but largely overlooked the crucial role of environmental and ecological traits in contaminant accumulation (Djedjibegovic et al., 2020; Herceg Romanić et al., 2021). Some studies have only evaluated the heavy metal health risks of aquatic products while ignoring the health benefits of aquatic products, failing to conduct comparative analysis to determine the net benefits (Chen et al., 2019; Zhang et al., 2021). Some regional studies that generalize from scant aquatic species and small samples exaggerate the public health risks of aquatic foods (Cobbinah et al., 2025; Islam et al., 2016), may erode consumer trust and cut essential nutrients intake, ultimately harming public health (Oken et al., 2012; Troell et al., 2019). Some studies have provided dietary guidelines for species consumption limits, but these are either risk-based limit that only consider contaminant exposure and acceptable risk thresholds without considering nutritional benefits (FDA, 2022; Lin et al., 2021), or risk–benefit-based limit that determine intake levels where health risks equal nutritional benefits through quantitative analysis (FAO/WHO, 2011; Gao et al., 2015). The differences in consumption limits resulting from methodological variations may confuse consumers' decision-making processes, thereby affecting the scientific basis of their rational dietary choices. Moreover, there is a lack of systematic assessments integrating heavy metal exposure risks with aquatic food consumption patterns, socioeconomic factors, and quantitative risk evaluations across multiple nations and populations. This lack of a holistic, global perspective has hindered the development of effective strategies to mitigate the potential health risks associated with heavy metal contamination in aquatic foods.

This study aims to present the first comprehensive global-scale assessment of heavy metal contamination in aquatic foods, focusing on mercury, cadmium, lead, and arsenic. By analysing 138,281 test records from the WHO's Food Safety Collaborative Platform (FOSCOLLAB) database (WHO, 2018a), applying the FAO/WHO and FDA's species classification framework for risk reduction (FAO/WHO, 2011; FDA, 2021b), and incorporating FAO's global aquatic foods consumption data (FAO, 2024a), this study aims to assess the global health risks associated with heavy metals in aquatic foods and develop effective risk mitigation strategies. The WHO database is dedicated to those involved in food risk analysis to support food safety decision-making with a big data approach (Marvin et al., 2017). Experimental studies are limited by researchers' geographic location, funding, and accessibility, typically involving dozens to hundreds of samples (Djedjibegovic et al., 2020; Rakib et al., 2021; Saha et al., 2016), while traditional *meta*-analyses usually rely on up to thousands of samples but tend to focus on or be limited to specific countries or specific species (Huang et al., 2019; Umeoguaju et al., 2023; Xiang et al., 2024). Moreover, studies with significant results, conforming to expected hypotheses, or from prestigious institutions are more likely to be published, creating publication bias issues that may systematically distort the conclusions of *meta*-analyses (Lin and Chu, 2018). The extensive records in the WHO database, collected using standardized protocols and rigorous quality assurance measures, enable us to conduct more comprehensive, globally representative analyses.

Our research objectives are multifaceted (Supplementary Fig. 1): First, to assess heavy metal concentrations in different aquatic species and calculate the compliance rate; second, to investigate the influence of taxonomy, environmental and ecological traits on heavy metal accumulation patterns in aquatic organisms; third, to quantify potential health risks from heavy metal exposure at both global and national levels. Fourth, to quantify the benefits of aquatic products and compare them against health risks from heavy metal exposure to weigh the net benefits. Additionally, we aim to develop a risk-based classification system for aquatic foods that considers heavy metal concentrations and recommends maximum intake levels. Finally, we evaluate consumer risks and the effectiveness of strategies to avoid high-risk species through scenario analysis and Monte Carlo simulations.

By addressing these objectives, our study seeks to bridge existing knowledge gaps and offer a holistic, global perspective on the challenges of heavy metal contamination in aquatic foods. This endeavour is designed to lay the groundwork for targeted interventions and informed policy decisions, providing crucial insights to refine public health guidelines, data-driven strategies, industry practices, and consumer choices, all aimed at safeguarding human health while supporting the sustainable consumption of aquatic foods as vital nutritional resources.

2. Results

2.1. Species and geographic variability in heavy metal concentrations

Heavy metal concentrations vary significantly among aquatic species. We found that mercury levels in fish, cadmium and lead levels in molluscs, cadmium levels in cephalopods, and arsenic levels in molluscs were notably higher than in other categories (Fig. 1). Fish species, especially sharks, rays, flounder, and tuna, had significantly higher mercury levels than cephalopods, crustaceans, and molluscs ($P = 0.000$). Molluscs and cephalopods had significantly higher cadmium levels than crustaceans and fish ($P = 0.000$), with scallops, oysters, and squids showing the highest concentrations. Additionally, molluscs had significantly higher lead and arsenic concentrations than fish, crustaceans, and cephalopods ($P = 0.000$), with clams, oysters, and mussels identified as having high lead and arsenic levels at the species level.

Our analysis revealed distinct spatial patterns in heavy metal contamination across different regions (Supplementary Fig. 2). Two-

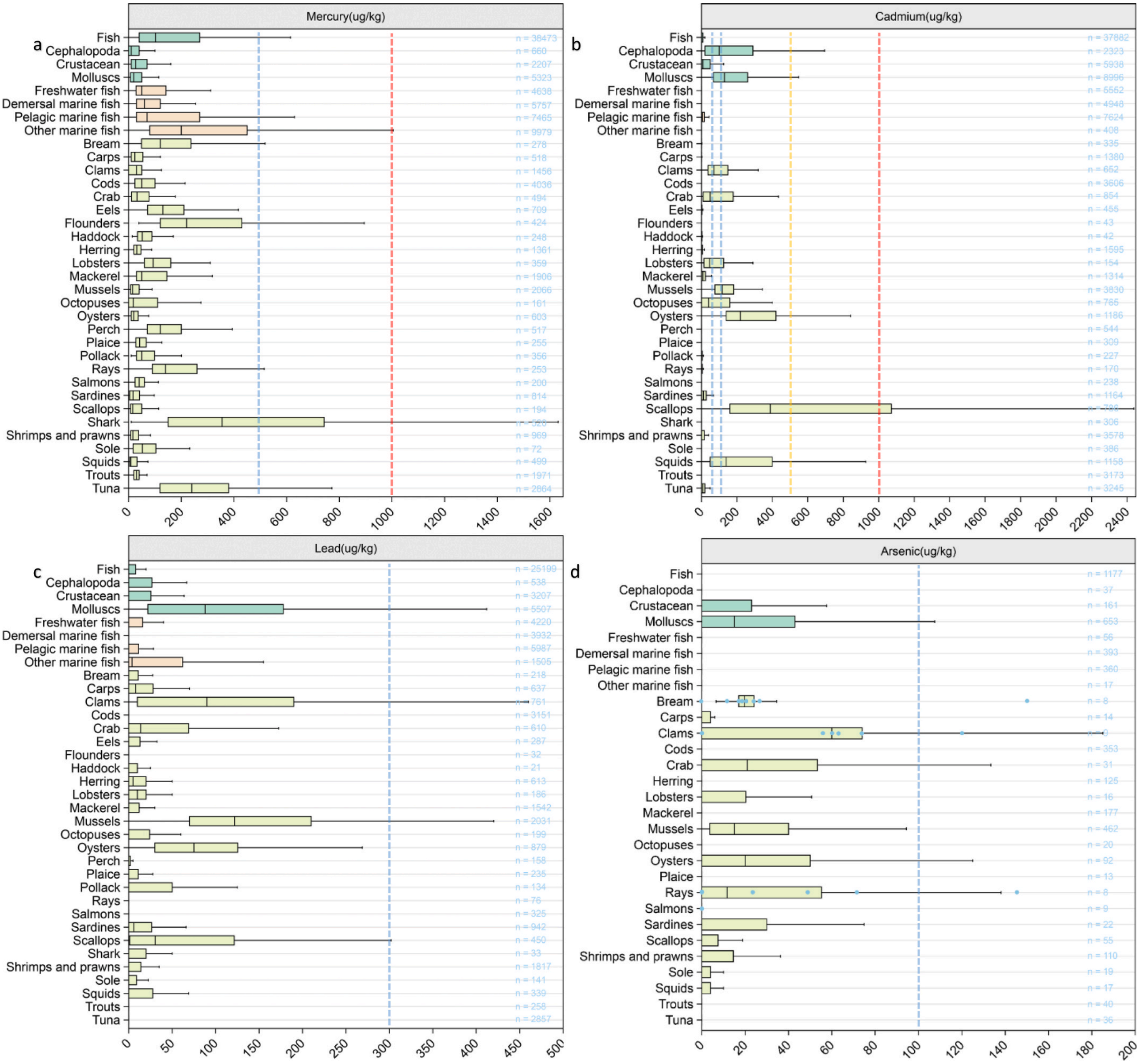


Fig. 1. Comparative analysis of heavy metal concentrations in aquatic species and species categories. a, Mercury. b, Cadmium. c, Lead. d, Arsenic. The vertical dashed lines denote the Maximum Residue Levels (MRLs) defined by food safety standards. Multiple lines indicate various MRLs for different aquatic foods: the blue line for low levels, the yellow line for medium levels, and the red line for high levels (Supplementary Table 1). In box plots, the centre line indicates the median, box limits indicate the first and third quartiles and the whiskers indicate the data range. The cyan box plots represent species categories, beige represents species subcategories, and light green represents individual species.

factor analysis indicates that both species and geographical variation influence heavy metal concentrations in aquatic food products. For mercury, we found that the combined effect of species and geography (i.e., how specific species accumulate mercury differently in different locations) has the strongest influence on contamination levels. In contrast, species type alone is the dominant factor determining cadmium, lead, and arsenic levels (Supplementary Fig. 3), suggesting that biological factors generally play a more significant role than geographic location in determining contamination levels. However, this pattern differs for fish, where geographical variation exerts influence comparable to species variation on heavy metal levels.

2.2. *Compliance with safety standards*

We calculated the proportion of samples with heavy metal concentrations below established food safety standards and found that 97.6 % of aquatic food samples were compliant. Molluscs had a higher compliance rate (97.9 %) than fish (97.7 %), crustaceans (97.0 %), and cephalopods (94.8 %). For individual heavy metals, the compliance rates were 96.2 % for mercury, 97.2 % for cadmium, 99.6 % for lead, and 99.5 % for arsenic (Supplementary Fig. 4, Supplementary Table 2).

Species with compliance rates below 90 % include bream, flounder, mackerel, salmon, and sharks for mercury; scallops, crabs, and squid for cadmium; and bream and rays for arsenic. We also observed regional differences in heavy metal content in aquatic products (Supplementary

Fig. 5, Supplementary Table 3). Except for Mauritius, all countries had heavy metal compliance rates above 90 %. In terms of specific metal compliance rates, Spain and Hong Kong had cadmium compliance rates below 90 %, while China and Singapore had lead compliance rates in aquatic products above 90 % but far below the overall compliance rate. Furthermore, we found that among European countries (Supplementary Fig. 6), Southern European countries generally had higher heavy metal content, with Spain, Italy, Greece, and Malta having compliance rates of only 91.7 %, 96.1 %, 95.8 %, and 95.8 % respectively, which were below the overall average. Many Northern European countries had higher compliance rates, such as Denmark at 99.3 %, Norway at 98.6 %, Sweden at 100 %, and Finland at 98.5 %.

2.3. *Environmental and ecological traits influencing heavy metal accumulation*

The Random Forest models used to analyse the influence of environmental and ecological traits on heavy metal accumulation in aquatic species demonstrate reasonable performance (Supplementary Table 4). Trophic level emerged as the most important predictor for mercury, cadmium, arsenic, and lead concentrations in aquatic products, followed by age at first maturity (Fig. 2). Trophic level, age at first maturity, fishing vulnerability score, and maximum length showed significant positive correlations with mercury concentration, indicating that large, long-lived top predators at high trophic levels contain higher mercury levels. However, conversely, trophic level, maximum length, and Demersal/Pelagic showed significant negative correlations with cadmium, lead, and arsenic, indicating that benthic organisms at low trophic levels, such as crustaceans and molluscs, typically contain higher levels of these metals. Feeding path showed negative correlations with lead and arsenic, indicating that species with benthic feeding pathways contain higher levels of lead and arsenic. Additionally, cadmium and lead showed negative correlations with species' fishing vulnerability score but positive correlations with resilience.

When only focusing on fish (Supplementary Fig. 7), resilience was the most important indicator for predicting heavy metal concentrations, followed by body size and trophic level. Trophic level, age at first maturity, fishing vulnerability score, and maximum length showed significant positive correlations with mercury, arsenic, and lead concentrations, but negative correlations with resilience. Demersal/Pelagic and feeding path were important indicators affecting cadmium and showed positive correlations with cadmium, indicating that pelagic fish that feed on pelagic aquatic organisms have higher cadmium content. Furthermore, growth coefficient showed positive correlations with mercury and arsenic but negative correlations with cadmium.

2.4. *Human exposure and health risks*

Globally, marine fish accounted for 56.0 % of mercury intake from aquatic food consumption, with contributions from pelagic fish (27.2 %), demersal fish (12.2 %), and other marine fish (16.7 %). Freshwater fish accounted for 40.4 % of global mercury intake, followed by crustaceans (2.4 %), molluscs (0.7 %), and cephalopods (0.5 %). Molluscs and cephalopods contributed 37.0 % and 29.1 % of global cadmium intake, respectively. Freshwater fish accounted for 42.6 % of global lead intake. Other marine fish, crustaceans, and molluscs contributed 27.7 %, 26.6 % and 20.5 % of global arsenic intake, respectively (Fig. 3a). These aquatic foods contributed to an estimated global intake of 12.1 tonnes of mercury (95 % CI: 11.7–12.5), 1.7 tonnes of cadmium (95 % CI: 1.6–1.8), 1.8 tonnes of lead (95 % CI: 1.6–2.0), and 0.4 tonnes of arsenic (95 % CI: 0.2–0.9, inorganic).

Mercury accounts for 97.2 % of the global Targeted Hazard Quotient (THQ). Marine fish were identified as the primary contributor to THQ related to mercury intake (Fig. 3b). Cadmium and arsenic are the predominant contributors to global Carcinogenic Risk (CR). Molluscs, crustaceans, and cephalopods emerged as the principal contributors to the CR from cadmium. In contrast, molluscs, crustaceans, freshwater fish, and other marine fish were identified as the primary sources of CR associated with arsenic exposure (Fig. 3c).

2.5. *National and regional variations*

Our national-scale assessment of heavy metal intake risk across 224 countries and regions revealed that the exposure risks, based on global average heavy metal concentration levels and national per capita aquatic food consumption, fell within acceptable ranges for 152

Fig. 2. Environmental and ecological traits as predictors of heavy metal concentrations in aquatic organisms. The bar length indicates the importance of each ecological predictor in estimating heavy metal concentrations, measured as the percentage increase in mean-squared error (Increase in MSE, %). The heatmaps present Pearson correlation coefficients between ecological predictors and heavy metal concentration, where colour intensity and hue indicate the strength and direction of the correlation. Significant correlations are overlaid with symbols (***, **, *) on the heatmap based on *P*-values (0.001, 0.01, 0.05).

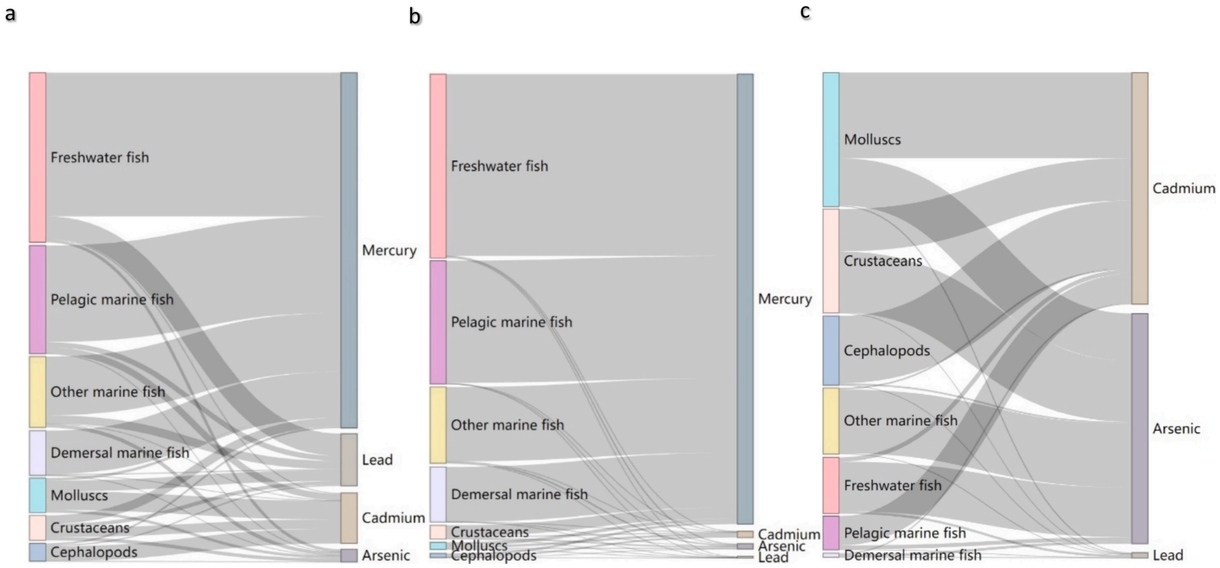


Fig. 3. Global heavy metal intake and associated health risks from aquatic foods categorised by species and specific metals. a, Estimated daily intake (EDI). b, Targeted hazard quotient (THQ). c, Carcinogenic risk (CR). Pelagic marine fish, demersal marine fish, and other marine fish are subcategories of the marine fish category.

countries and regions. Twenty-nine countries had mercury EDI exceeding the reference values, 69 countries had mercury THQ exceeding the limit value, 20 had cadmium CR exceeding the limit value, and 16 had arsenic CR exceeding the limit value (Fig. 4a).

Freshwater fish is the most consumed aquatic food source in 55 countries, including China and India, and freshwater fish is the primary source of mercury (39 countries), lead (73 countries), and arsenic (46 countries) among all aquatic food. Marine fish is the most important aquatic food source for 169 countries, and marine fish is the main source for mercury intake in 189 countries, cadmium (129 countries), lead (138 countries), and arsenic (128 countries) among all aquatic foods. Molluscs and crustaceans also contributed significantly to cadmium and arsenic intake in some countries (Fig. 4b).

Insights from the Random Forest model indicate that per capita aquatic food consumption, the ratio of coastline length to country area ($m\ km^{-2}$), and economic income levels show positive associations with heavy metal intake risks (Supplementary Fig. 8). Oceania consumed more aquatic foods than other continents, leading to elevated heavy metal exposure levels. Conversely, many African nations demonstrate minimal aquatic food consumption and consequently lower risk profiles. Island nations or countries with extensive coastlines relative to their land area often have elevated aquatic food consumption, resulting in heightened heavy metal exposure.

Among the six key aquatic food-consuming countries and regions, the European Union (EU) and the United Kingdom (UK) preferred marine fish, whereas China and India preferred freshwater fish. Consequently, these species categories are significant sources of heavy metal intake (Supplementary Fig. 9). Some species categories have disproportionately high heavy metal intakes despite low consumption volumes. For instance, although cephalopods represent a small fraction of aquatic food consumption, they account for a significant portion of cadmium intake in the Association of Southeast Asian Nations (ASEAN) and the EU. Meanwhile, though minor in the aquatic food supply compared to freshwater fish, molluscs are China's primary source of cadmium intake. Crustaceans consumed in the UK and the US, while constituting a smaller share of aquatic foods, are major sources of cadmium and arsenic intake.

2.6. Risk and benefit assessment

Globally, 143 countries and regions can achieve a daily intake of 250 mg of EPA and DHA per capita through aquatic food consumption. If this intake level is maintained throughout a lifetime, it could prevent 39,816 cardiovascular disease deaths per million people (Fig. 5). However, many inland countries in Asia and Africa still have room for improvement in reducing cardiovascular disease deaths due to insufficient aquatic food consumption.

The cancer mortality rate caused by cadmium, lead, and arsenic intake from aquatic food consumption is relatively low, with Macao having the highest rate among all countries and regions at 40 deaths per million people over a lifetime. However, the cancer mortality rate caused by heavy metal exposure is only one-thousandth of the cardiovascular disease mortality rate that can be prevented by aquatic foods, and all countries can save population lives through the consumption of aquatic foods.

In 153 countries, pregnant women could potentially increase their newborns' IQ by 5.8 points through EPA and DHA based on average national aquatic food consumption levels. In 49 countries, IQ decline due to mercury exposure from aquatic food consumption exceeded 1 point, with Kiribati showing the highest IQ decline of 3.13 points from mercury exposure through aquatic food consumption, yet still achieving a net IQ gain of 2.67 points. Although mercury intake from aquatic food consumption leads to IQ decline, the EPA and DHA intake from aquatic food consumption also results in IQ improvement. All countries achieved net positive IQ gains through aquatic food consumption.

2.7. Consumer guide

We determine the maximum consumption levels for different species through health risk and risk–benefit assessment, identifying high-risk species to provide consumption guidance to consumers. We use BRQ (Benefit-Risk Quotient) to evaluate the risk and benefit profiles of aquatic species, and provide maximum aquatic food intake levels FIR_{EDI}, FIR_{THQ}, and FIR_{CR} based on exposure, non-cancer, and cancer risk assessments, where the minimum value represents the risk-based consumption limit. We provide maximum aquatic food intake levels (FIR_{Deaths} and FIR_{IQ}) based on risk–benefit assessment of mortality and IQ, where the minimum of these two values represents the risk–benefit-based consumption limit. The specific calculation process and theory are detailed in the Methods section.

We found that all aquatic species had BRQ_{IQ} and BRQ_{Deaths} values below 1 (Supplementary Table 5), indicating that consuming aquatic

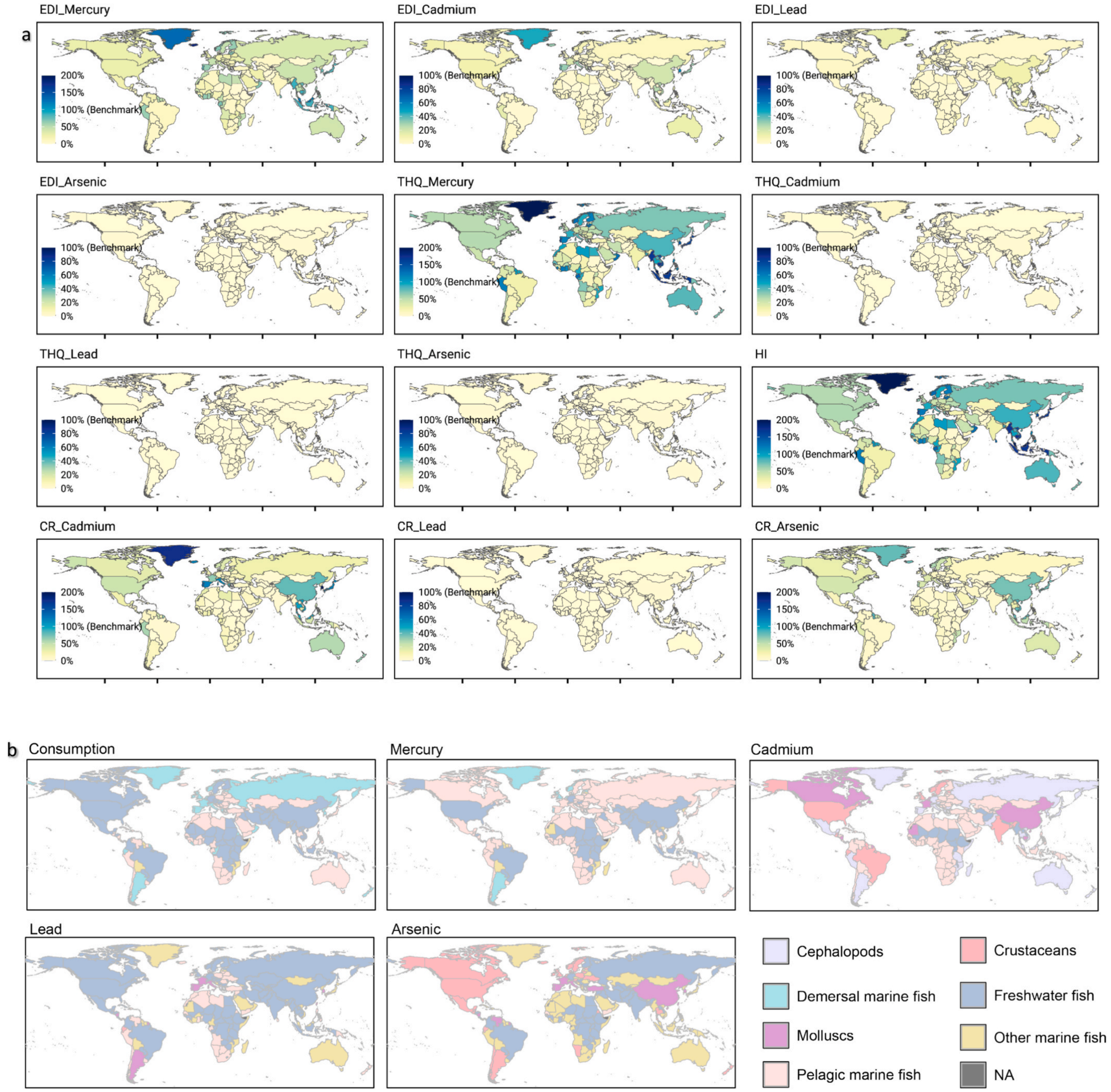


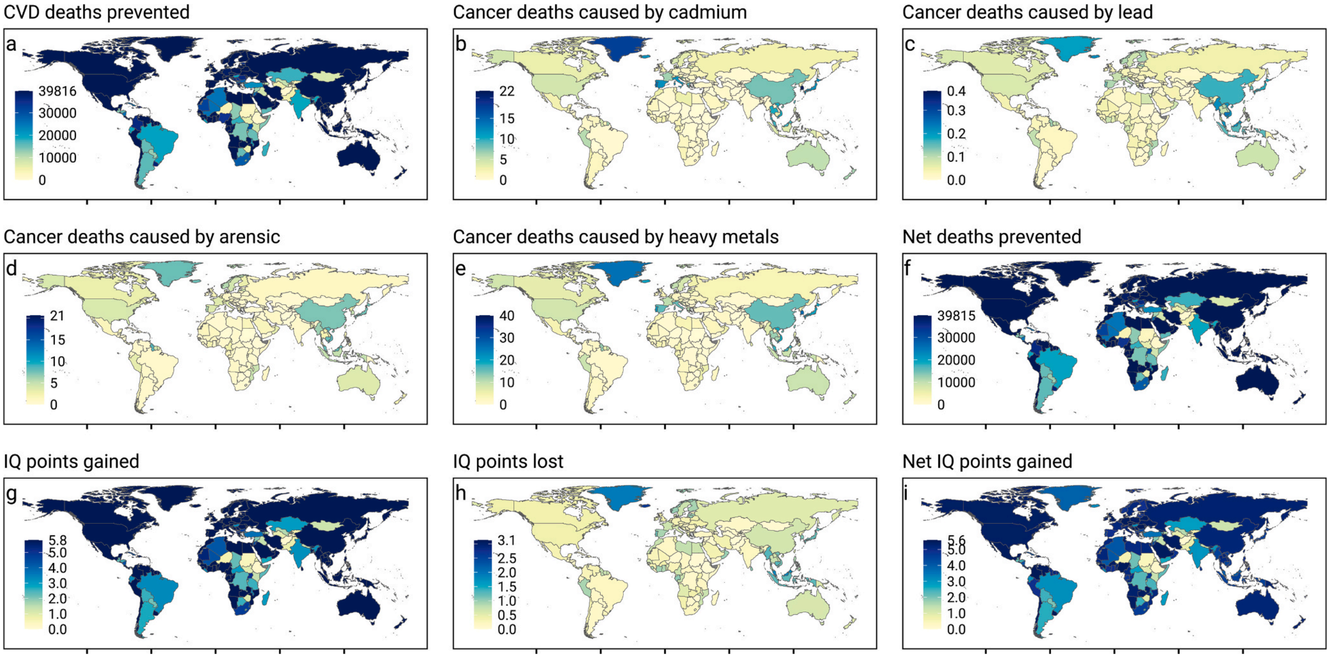
Fig. 4. Heavy metal intake health risks from aquatic foods across countries and regions. a, Risks measured by Estimated Daily Intake (EDI), Targeted Hazard Quotient (THQ), Hazard Index (HI), and Carcinogenic Risk (CR) of mercury, cadmium, lead, and arsenic. b, The dominating species category in aquatic food consumption and heavy metal intakes.

foods produces net benefits when not considering the upper limit of EPA + DHA benefits. Among BRQ_{IQ} values, shark had the highest at 0.54. Among BRQ_{Deaths} values, oyster had the highest at only 0.02. Compared to BRQ_{IQ}, BRQ_{Deaths} values were generally lower.

We found that the risk-based limits for all species are lower than the risk–benefit-based limits, and there are huge differences between the limits (Supplementary Table 6). Taking scallops and sharks as examples. For scallops, FIR_{EDI} is 9.5 g/day, FIR_{THQ} is 95 g/day, FIR_{CR} is 2.5 g/day, FIR_{IQ} is 2100.3 g/day, and FIR_{Deaths} is 9613.2 g/day. For sharks, FIR_{EDI} is 26.8 g/day, FIR_{THQ} is 14.1 g/day, FIR_{CR} is 506.6 g/day, FIR_{IQ} is 107.9 g/day, and FIR_{Deaths} is 1761788.1 g/day, with FIR_{THQ} and FIR_{Deaths} differing by five orders of magnitude.

The risk–benefit-based limit represents the upper limit of net beneficial consumption, while the risk-based limit can serve as the upper limit for safe consumption, and we found that the risk–benefit-based limit for aquatic foods always far exceeds the risk-based limit. Therefore, consumption below the risk-based limit is both safe and generates positive net benefits. Consumption between the risk-based limit and the risk–benefit-based limit still produces positive net benefits, but consumption exceeding the risk–benefit-based limit results in negative net benefits and typically leads to unacceptable health risks. Consumers can make informed choices based on these two limits.

Generally speaking, the aquatic foods risk–benefit-based limit is usually much higher than the consumer's actual aquatic foods consumption level. To provide a more conservative assessment of consumption risk, without considering nutritional impacts and considering



CVD deaths prevented

Cancer deaths caused by cadmium

Cancer deaths caused by lead

Cancer deaths caused by arensic

Cancer deaths caused by heavy metals

Net deaths prevented

IQ points gained

IQ points lost

Net IQ points gained

Fig. 5. Risk and benefit from aquatic foods consumption across countries. a, Cardiovascular disease deaths prevented per million people from aquatic food EPA + DHA intake. b, Cancer deaths caused per million people from aquatic food cadmium intake. c, Cancer deaths caused per million people from aquatic food lead intake. d, Cancer deaths caused per million people from aquatic food arsenic intake. e, Cancer deaths caused per million people from aquatic food heavy metal (cadmium, lead, and arsenic) intake. f, Net lives saved per million people from aquatic food consumption. g, IQ points gained from aquatic food EPA + DHA intake. h, IQ points lost from aquatic food mercury intake. i, Net IQ points gained from aquatic food consumption.

safety, we further recommended daily maximum intake determined by risk-based limit. The recommended maximum daily intake for each species is shown in Fig. 6. Additionally, we derived the following recommended daily maximum intake by edible weight (Fig. 6): for fish (marine and freshwater), 122.1 g person^{-1} day^{-1}; crustaceans, 37.3 g person^{-1} day^{-1}; molluscs, 6.9 g person^{-1} day^{-1}; cephalopods, 8.7 g person^{-1} day^{-1}; and weighted average, 108.7 g person^{-1} day^{-1}, based on the trimmed mean of heavy metal data (Supplementary Table 6). Using a more conservative approach with the upper 95th percentile CI of the mean, the recommended intakes are lower: fish, 82.8 g person^{-1} day^{-1}; crustaceans, 6.0 g person^{-1} day^{-1}; molluscs, 4.7 g person^{-1} day^{-1}; cephalopods, 5.9 g person^{-1} day^{-1}; and weighted average, 72.4 g person^{-1} day^{-1} (Supplementary Table 7). The variance between these two recommendations highlights the potential extremes and uncertainties associated with each category, with crustaceans, for instance, showing higher uncertainties than fish.

Mercury is the primary factor for exceeding risk-based limits and presenting high non-cancer risks in most fish species, determining their recommended daily maximum intake limits. Similarly, due to cancer risks, arsenic and cadmium play a decisive role in setting intake limits for crustaceans, molluscs, and cephalopods.

2.8. *Risk mitigation strategies*

Although we assessed heavy metal health risks based on national-level average consumption of aquatic products, this reflects risk levels at the national scale and often fails to accurately represent the actual health risks faced by individual consumers. Furthermore, while both FAO and FDA recommend that consumers limit their intake of high-risk aquatic products, there is still a lack of quantitative analysis regarding the effectiveness of strategies to reduce consumption of high-risk aquatic products. To address these gaps, we conducted further analysis at the individual consumer level across countries using Monte Carlo simulation.

We first categorised aquatic foods into three categories (Fig. 6) based on their recommended daily maximum intake by edible weight: The vertical lines indicate the global average (40 g person-1 day^{-1}) and half the global average (20 g person^{-1} day^{-1}) consumption rates of edible aquatic foods (Naylor et al., 2021). 'Best Choices' for low-risk foods with a recommended daily maximum intake $\geq$ 40 g person^{-1} day^{-1}, 'Good Choices' for medium-risk foods with an intake of 20–40 g person^{-1} day^{-1}, and 'Choices to Control' for high-risk foods with an intake $<$ 20 g person^{-1} day^{-1}. A substantial 71.4 % of edible production falls into the low-risk 'Best Choices' category, followed by 17.6 % classified as medium risk 'Good Choices', and 11.0 % as high risk 'Choices to Control'.

Monte Carlo simulation results indicate that reducing consumption of aquatic products with high levels of heavy metal pollutants can effectively reduce health risks. In the baseline 'Business as Usual' (BAU) scenario, 16.1 % of the simulated global population is expected to exceed the exposure risk thresholds. Adopting the 'Limit Worst' strategy, which involves consuming medium and low-risk aquatic foods, reduces this proportion to 9.3 %, while the 'Only Best' scenario, advocating for the consumption of exclusively low-risk aquatic foods, further lowers it to 6.2 % (Fig. 7, Supplementary Fig. 10).

Regarding non-cancer risks, the BAU scenario forecasts 15.0 % of the population at high risk. The 'Limit Worst' strategy raises this proportion to 16.4 %, while the 'Only Best' strategy decreases it to 12.3 %. The 'Limit Worst' strategy slightly increased the non-cancer risk due to the higher mercury levels in medium and low-risk aquatic foods compared to those in the high-risk category. For cancer risks, the simulations predicted 27.6 % of the population to be at high risk under the BAU scenario, with 18.3 % for cadmium and 13.0 % for arsenic. Implementing the 'Limit Worst' and 'Only Best' strategies would reduce these proportions to 7.2 % (3.4 % for cadmium and 4.2 % for arsenic) and 5.9 % (1.9 % for cadmium and 4.2 % for arsenic), respectively.

3. Discussion

3.1. *Aquatic food compliance and human activity*

Our research indicates that heavy metal concentrations in aquatic foods generally remain below the maximum residue level critical

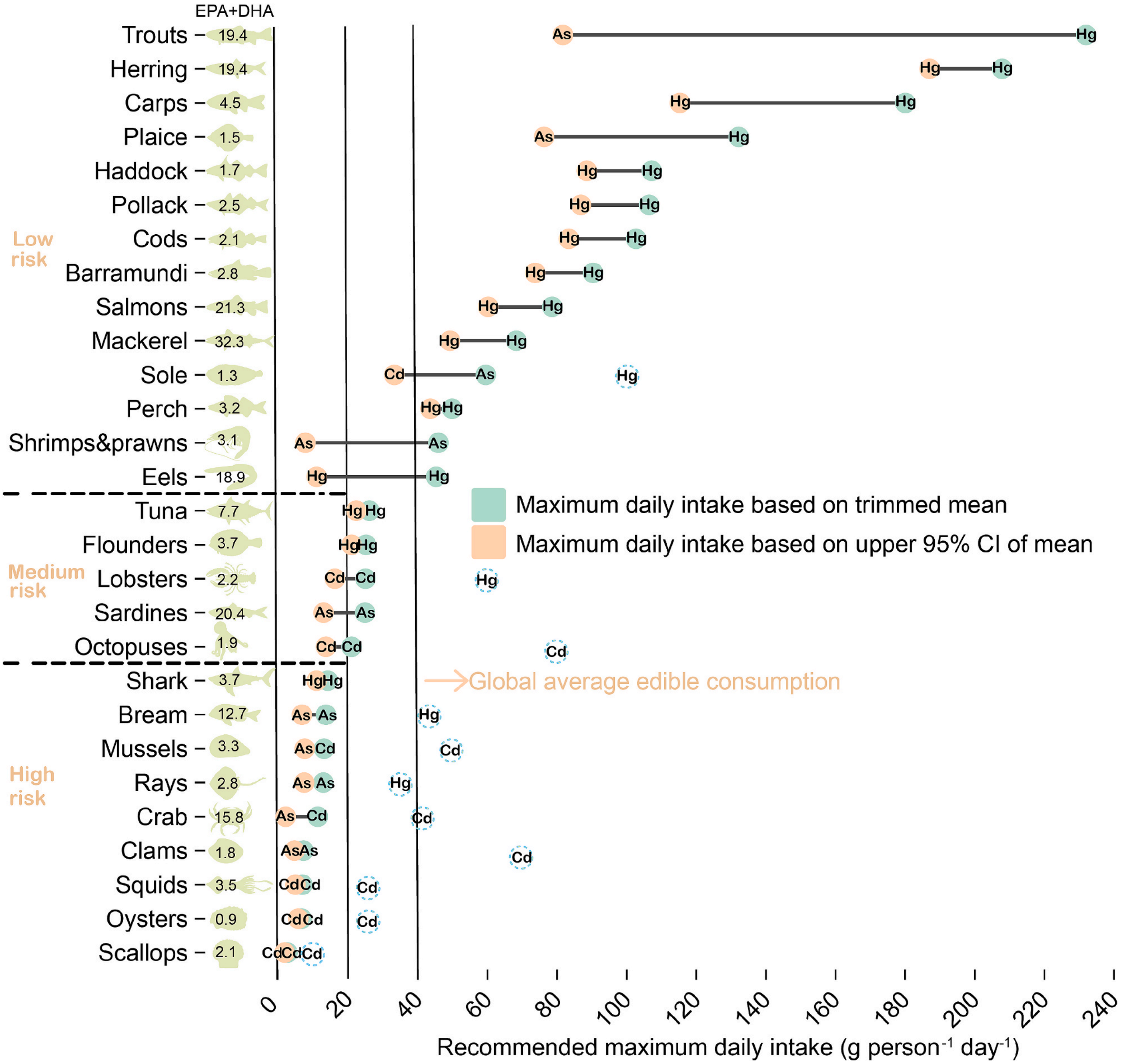


Fig. 6. Risk-based recommended maximum daily intake levels by edible weight for aquatic foods. The values in the aquatic species images represent the EPA + DHA content (mg/g). The recommended maximum daily intakes, marked by green and orange spots on the figure, are based on predefined health risk benchmarks (e.g., EDI = reference values, THQ = 1.0, CR = 0.00001). Green spots denote recommendations based on the trimmed mean of heavy metal concentrations, whereas orange spots are based on the upper 95th percentile confidence interval (CI) of the mean. The heavy metal abbreviations marked on the spots (Hg for mercury, Cd for cadmium, As for arsenic) indicate the heavy metal limiting the recommended maximum daily intake levels. The distance between the green and orange spots represents the degree of uncertainty in the concentrations of heavy metals. The blank spots with surrounding dashed lines represent the recommended maximum daily intake calculated using a less stringent benchmark (CR = 0.0001). Only data points for the recommended maximum daily intake based on this less stringent benchmark, where the intake is less than 240 g, are illustrated in the figure. The vertical lines indicate the global average (40 g person^{-1} day^{-1}) and half the global average (20 g person^{-1} day^{-1}) consumption rates of edible aquatic foods. Aquatic foods are defined as 'Best Choices' for low-risk foods with a recommended daily maximum intake ≥ 40 g person^{-1} day^{-1}, 'Good Choices' for medium-risk foods with an intake of 20–40 g person^{-1} day^{-1}, and 'Choices to Control' for high-risk foods with an intake < 20 g person^{-1} day^{-1}.

thresholds on a global scale. Compared to red meat, which commonly exceeds standards for lead and cadmium content (Salim et al., 2023), aquatic foods have a relatively high heavy metal food safety compliance rate of 97.6 %. However, it should be noted that regulatory limits for heavy metal concentrations in aquatic foods are not consistent, and aquatic foods with higher heavy metal content usually align with the higher limits permitted in food safety standards (Djedjibegovic et al., 2020). Even when compliant with food safety standards, may still pose health risks (Wei et al., 2023). For example, although tuna has higher mercury content, its mercury compliance rate is even higher than the overall mercury compliance rate for aquatic foods, because the maximum residue limit for mercury in tuna is higher than for other species (The European Commission, 2023).

Global heavy metal geochemical mapping research indicates that human activities have greatly intensified pollution levels and reveals a “metal-rich corridor” running through the major cradles of ancient human civilizations (ancient Greek civilization, the Roman Empire, Persian culture, ancient India, and the Yangtze River Basin civilization of China) (Hou et al., 2025). We found aquatic products from Spain, Greece, Italy, and China have relatively low heavy metal compliance

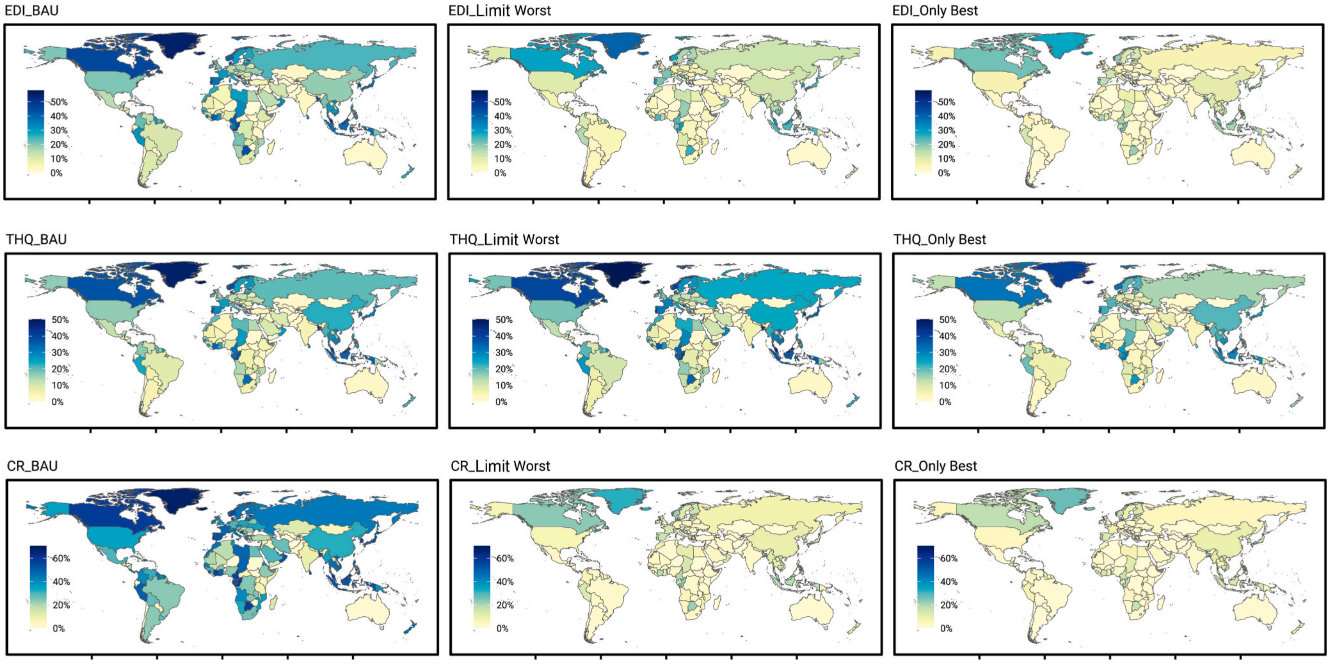


Fig. 7. Proportion of the population (%) exposure to high risks from four heavy metals (mercury, cadmium, lead, and arsenic) in the three scenarios (’Business as Usual’ (BAU), ’ Limit Worst’, and ’Only Best’). a, Estimated daily intake (EDI). b, Targeted hazard quotient (THQ). c, Carcinogenic risk (CR). The ’BAU’ scenario assumes unchanged consumption patterns of all aquatic foods. The ’Limit Worst’ scenario encompasses the consumption of both medium-risk, ’Good Choice’ and low-risk, ’Best Choice’ categories. In contrast, the ’Only Best’ scenario presupposes consuming only the low-risk, ’Best Choice’ aquatic foods.

rates, particularly in Southern Europe where aquatic product heavy metal compliance rates are generally lower than those in Northern Europe, this pattern is consistent with existing global and EU soil heavy metal concentrations and compliance rates (Hou et al., 2025; Tóth et al., 2016), indicating that aquatic food contamination is not an isolated phenomenon, but rather an extension of terrestrial environmental burden into freshwater and marine systems.

Human activities including industrial emissions, intensive agriculture, and solid waste disposal continuously release heavy metals into the environment (Fig. 8), where they undergo complex transport and transformation processes as dissolved ions that travel long distances through surface runoff and groundwater, as adsorbed particles that accumulate in sediments and enrich downstream soils, and as contaminants carried by rivers to marine environments where aquatic organisms in estuarine zones absorb and concentrate them (Liu et al., 2021; Mititelu et al., 2025). Heavy metal-containing fertilizers and pesticides applied in agricultural activities can migrate to adjacent surface water bodies through surface runoff or drainage systems during heavy rainfall or irrigation, becoming a potential source of heavy metals in aquaculture ponds and rivers (Madjar and Vasile Scăețeanu, 2025; Sun et al., 2020).

3.2. Heavy metals trophic transfer

Random forest model results indicate that trophic level is the primary predictor of heavy metal concentrations in aquatic organisms. Mercury concentrations show a significant positive correlation with trophic level. Conversely, cadmium, lead, and arsenic concentrations exhibit negative correlations with trophic level. The fundamental causes of these differences lie in the physicochemical properties of heavy metals and the tissue metabolic characteristics of organisms (Luoma and Rainbow, 2005). Before detailing these differences, it is useful to clarify some key terms (see glossary).

Bioaccumulation of metals in aquatic organisms proceeds via two

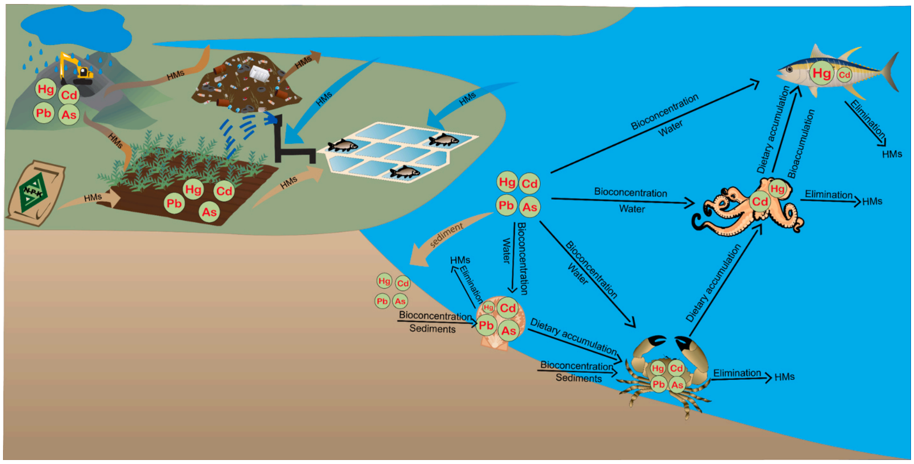


Fig. 8. The concept of heavy metal pollutants transport and aquatic food chain transfer.

main routes (Fig. 8): (1) direct uptake from water and sediments (bioconcentration), and (2) food-web transfer through predator–prey interactions (biomagnification), with both routes being offset by elimination (Ali and Khan, 2019). The following equation summarizes bioaccumulation: Bioaccumulation = bioconcentration + food chain transfer – (elimination + growth dilution) (Ali and Khan, 2019; Yarsan and Yipel, 2013).

Methylmercury readily crosses cell membranes and binds to intracellular thiols, forming trapped complexes that clear slowly, leading to long-term buildup in the liver, muscle, and brain (Bridges and Zalups, 2017; Hong et al., 2012). High-trophic-level cephalopods and fish, inhabiting pelagic waters, accumulate metals mainly through bioconcentration from water and dietary accumulation. Experimental research shows that, as body size increases, aquatic organisms display decreased aqueous uptake rates of mercury, increased dietary assimilation efficiencies of Hg, and lower efflux rates (Dang and Wang, 2012). Methylmercury is biomagnified in trophic transfer primarily through dietary accumulation. Therefore, larger, late-maturing (usually longer-lived) high trophic level aquatic species (such as sharks, tuna, and rays) have higher mercury content due to long-term dietary accumulation (Blanchfield et al., 2022). However, farmed fish like carps and trouts typically have lower mercury levels (Fig. 1) due to shorter growth cycles and because artificial feed contains binding agents and indigestible materials that slow mercury release compared to soft-bodied prey, resulting in lower mercury assimilation efficiency (Bowling et al., 2011; Dutton and Fisher, 2010).

Low trophic level molluscs and crustaceans inhabit the sediments surface and efficiently bioconcentrate heavy metals from water, sediments, and diet due to high uptake rates and low excretion (Wang and Rainbow, 2008; Zhang et al., 2022c). Conversely, high trophic level species are sediment-distant with lower uptake and assimilation efficiency for cadmium, lead, and arsenic, resulting in decreased trophic transfer efficiency and biodilution phenomena (Saidon et al., 2024; Zhang et al., 2022c).

Species specificity also influences heavy metal content (Stevenson et al., 2025). Cephalopods are exceptional for cadmium enrichment, with nearly 100 % uptake efficiency, possibly due to high metallothionein expression and intracellular chelation (Bustamante et al., 2002), creates a single-step concentration increase in the food chain but doesn't constitute biomagnification (which requires at least two trophic transfers) (Ali and Khan, 2019). Pelagic marine fish show higher cadmium levels than other fish, likely from feeding on high-cadmium cephalopods (Bustamante et al., 1998; Wang and Ke, 2002), supported by positive correlations between feeding patterns and cadmium content. Varying correlations between growth rates and different heavy metals suggest faster-growing organisms may consume more prey and thus accumulate more metals through diet, but rapid growth may also simultaneously dilute internal concentrations through growth dilution effects (Stevenson et al., 2025).

Our results and current research conclusions on heavy metal trophic transfer in aquatic organisms show that Hg exhibits typical biomagnification characteristics, while Cd, Pb and As typically exhibit biodilution or benthic enrichment rather than biomagnification (Ali and Khan, 2019; Cardwell et al., 2013; Saidon et al., 2024). Consuming high trophic level aquatic organisms may pose higher mercury exposure risks, while consuming low trophic level aquatic organisms may pose higher cadmium, lead, and arsenic exposure risks.

3.3. *Risk and benefit assessment conceptual framework*

Aquatic food risk assessments can mainly be divided into two categories. One category primarily focuses on health risk studies of lifelong cumulative exposure caused by environmental pollution (Han et al., 2020; USEPA, 2025). Such assessments are typically prevention-oriented, tend to adopt strict risk thresholds to prevent health hazards, and usually do not consider nutritional benefits. Regional or species-specific aquatic food studies typically use local sampling combined with consumption data to assess consumer exposure risk and compare it with established risk thresholds, thereby identifying high-risk regions and aquatic species to provide risk warnings for consumers (Cobbinah et al., 2025; Djedjibegovic et al., 2020). National or global studies, through *meta*-analysis and model construction, focus on elucidating the impact of existing pollution on human health, emphasizing the urgency of improving environmental quality (Chen et al., 2025; Zhang et al., 2021). The other category is risk and benefit assessment. FAO/WHO advocates for a comprehensive consideration that recognizes both risks and nutritional benefits, rather than relying entirely on conclusions from a single discipline (FAO/WHO, 2024). FAO/WHO established a risk–benefit assessment framework for aquatic products that adopts quantitative methods, using mortality and IQ scores as indicators to quantitatively compare risks and benefits, with net benefit as the determining factor (FAO/WHO, 2011). This assessment framework helps identify and screen high-risk species while providing net benefit information and consumption recommendations.

We believe that both health risk assessment and risk–benefit assessment have their roles. Building upon health risk assessment and FAO's previous framework that only included mercury and dioxins, we have constructed a conceptual framework for heavy metals risk and EPA + DHA benefit assessment in aquatic foods, as shown in Fig. 9. The benefits of EPA + DHA are manifested in two aspects (FAO/WHO, 2011): first, enhancing neural transmission, reducing inflammation and oxidative damage, and improving cognitive ability and IQ development; second, improving cardiovascular health and preventing cardiovascular disease deaths (Fig. 5). Aquatic foods are the primary EPA + DHA source (Hamilton et al., 2020), with oily fish being major contributors (Fig. 6). Aquatic food contains Hg, Cd, Pb, and As, but there are differences among species categories. Fish typically have significantly higher Hg concentrations than Cd, Pb, and As (Fig. 1), and due to high fish consumption (Fig. 4b), fish are the main source of consumer Hg intake (Fig. 3a). Shellfish have higher concentrations of Cd, Pb, and As than Hg (Fig. 1), making them the main source of consumer intake of these metals. Hg constitutes the primary non-cancer risk (Fig. 3b), while Cd, Pb, and As pose lower non-cancer risks but are sources of cancer risk (Fig. 3c). The main harm of Hg is neurological damage and impaired IQ development (Figs. 4,5), while intake of Cd, Pb, and As may lead to cancer deaths (Figs. 4,5). We found that the benefits of aquatic products in terms of IQ points and mortality are generally greater than the risks, and the number of deaths prevented by intaking EPA + DHA from consuming aquatic products far exceeds the cancer death risk caused by intaking heavy metals from consuming aquatic products (Fig. 5, Supplementary Table 6,7).

The risk-based versus risk–benefit-based limits are illustrated in Fig. 9b and c. In health risk assessment, health risk increases with increasing aquatic food consumption. When the risk level reaches a preset safety threshold, the corresponding consumption amount is the risk-based limit, and exceeding this limit may cause adverse effects on human health. In risk–benefit assessment, both the risks and benefits of aquatic food increase with consumption, and for the vast majority of species, the slope of the benefit line is greater, meaning benefits outweigh risks. However, when EPA + DHA daily intake reaches 250 mg, the health benefits tend to plateau, forming a benefit ceiling, while the intake of aquatic food contaminants continues to increase with higher consumption. When risk equals benefit, the corresponding consumption amount represents the risk–benefit-based limit, and when consumption exceeds this limit, the risks outweigh the benefits.

3.4. *Safe consumption*

We assessed the safety margin between safe consumption levels and current consumption levels. Without considering the health benefits of aquatic products or the effects of cooking methods (such as steaming and frying) on heavy metal bioavailability, the weighted safe consumption

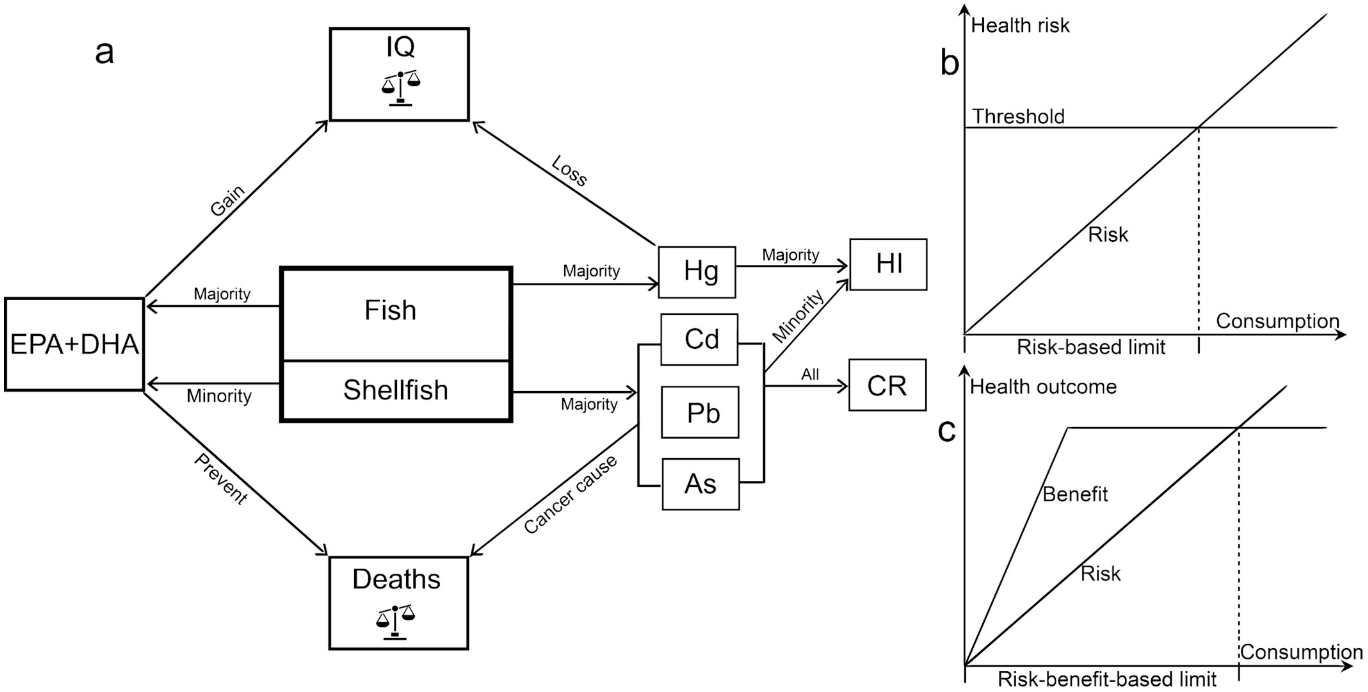


Fig. 9. A conceptual framework for assessing the risks (heavy metals) and benefits (EPA + DHA) of aquatic foods. a. Integrated health risk and benefit assessment model for heavy metals and EPA + DHA in aquatic foods. b. Aquatic foods risk-based limit calculated according to health risk assessment. c. Aquatic foods risk–benefit-based limit calculated according to risk and benefit assessment.

limit for aquatic products based solely on health risk assessment (108.7 g/day) far exceeds the current global average consumption level (40 g/day). This limit is 3.9, 1.9, and 1.6 times higher than the Lancet diet (28 g/day), flexitarian diet (58 g/day), and Mediterranean diet (70 g/day), respectively, and substantially exceeds the recommended intake levels in dietary guidelines from various countries including China (40–75 g/day), India (14.3–28.6 g/day), the United States (32.3 g/day), and the United Kingdom (40 g/day) (Zhu et al., 2023).

However, the recommended maximum daily intake varies among different aquatic foods. We have identified medium and high-risk species as well as metal risk sources based on current consumption levels. This risk-based classification system aims to provide clear labelling and communication strategies, which are particularly important for vulnerable groups such as pregnant women and children who may face higher health risks (FDA, 2022). We validated the effectiveness of substituting low-risk species to reduce high-risk exposure through Monte Carlo simulation and scenario assumptions. Under the “Only best” scenario, the proportion of the population exceeding exposure risk thresholds decreased from 16.1 % to 6.2 %, validating the effectiveness of substituting high-risk species and providing evidence-based support for global policy interventions and public health recommendations.

3.5. Risk monitoring and control

While obtaining nutritional and health benefits from consuming aquatic foods, it is crucial to establish an effective regulatory and risk management system. Key measures include but are not limited to: international regulatory regulations setting MRL for heavy metals, particularly targeting high-exposure contribution foods to reduce consumer exposure risks (Satarug and Moore, 2004; Wong et al., 2022); governments and research institutions conducting health risk assessments and balancing nutritional benefits based on local heavy metal pollution characteristics, aquatic foods nutritional components, and population consumption habits to formulate consumption guidance principles (FAO/WHO, 2024); consumer education should cover differences in heavy metal content among different species and guide the limitation of high-risk aquatic foods intake (Bosch et al., 2016; Zhao et al., 2023); establishing a risk–benefit based classification labeling system that promotes rational consumer choices through clear labels and communication strategies (FAO/WHO, 2011; FDA, 2022).

Existing research shows that pollution control policy changes can effectively improve heavy metal safety risks in aquatic foods (Blanchfield et al., 2022; Cai et al., 2025). Fisheries and aquaculture should adopt best practices to minimize heavy metal risks in aquatic foods. Recommended measures include: avoiding establishing aquaculture farms in areas known to have severe heavy metal contamination (Abbas et al., 2024; Li et al., 2023); regularly testing local aquatic food tissues, water bodies, and sediments to ensure they meet standards (Djedjibegovic et al., 2020; Webb et al., 2020); using biological filters and aquatic plants that can effectively remove heavy metals (Bhat et al., 2022); and collaborating with other sectors such as agriculture and mining to jointly mitigate the impact of upstream heavy metal pollution sources (Cai et al., 2025; Hou et al., 2025; Sodango et al., 2018).

Heavy metal risk in aquatic foods may change with variations in species and production methods (Chen et al., 2025). We found that although freshwater fish supply a larger global edible quantity (Zhang et al., 2022b; FAO, 2024a), marine fish with higher concentrations contribute more to mercury exposure, consistent with findings from previous research (Zhang et al., 2021). As freshwater aquaculture fish become more prevalent in aquatic foods, their shorter life cycles and lower trophic levels reduce mercury accumulation, leading to a decline in mercury-related health risks (Zhang et al., 2022a). Meanwhile, molluscs and crustaceans are occupying an increasingly larger share of aquatic food production (FAO, 2024a), and consumers are also increasingly preferring to consume molluscs and crustaceans (Xu et al., 2024), which may increase consumers’ cancer risk from heavy metals. For example, in China, the average consumption of molluscs is 8 times the global average (FAO, 2024a), leading to relatively high cancer death risk (Fig. 4a, b). The cadmium risk from aquatic food consumption has even exceeded that from grains, becoming the primary source of cadmium exposure for residents, and shows a gradually increasing trend that deserves attention (Qing et al., 2020).

International trade redistributes heavy metal exposure risks across borders (Chen et al., 2025; Muir, 2020). Given that over one-third of aquatic food products enter global trade and many countries heavily depend on imported consumption (FAO, 2024b; Shamshak et al., 2019), this means that attention should not be limited solely to sampling domestic products. It is necessary to strengthen monitoring and regulation of aquatic product safety issues in international trade, and increase investment in food safety and health-related institutions to improve supply chain traceability and safeguard public health (Love et al., 2021b).

4. Uncertainty and limitations

In our assessment aimed at reducing risk, we opted for a conservative cancer risk reference value of 1 in 100,000 ($CR \leq 0.00001$) (Rakib et al., 2021; Saha et al., 2016), which is stricter than the 1 in 10,000 ($CR \leq 0.0001$) threshold used in certain studies (Wang et al., 2020). For IQ points, we used the upper limit value of 0.7 IQ points reduction per microgram/gram increase of mercury in hair in our calculation formula for assessment. These decisions align with adopting a cautious approach towards public health and safety. Switching the reference value from 1 in 100,000 to 1 in 10,000 would decrease the percentage of the global population at high cancer risk under the current business-as-usual (BAU) scenario from 27.6 % to 4.3 % (Supplementary Fig. 10). Consequently, the recommended maximum consumption limits for some aquatic foods (especially molluscs) will increase, and the heavy metal that restricts consumption of lobster, sole, rays, and bream has also changed to mercury (Fig. 6). If the central estimate value of 0.18 were used for IQ point assessment, the IQ point loss results would become one-fourth of the original, while the net benefits of aquatic food consumption would increase (Supplementary Fig. 11). These uncertainty assessments reveal the potentially enormous impact that differences in parameters used across different risk assessment studies may have on results and conclusions.

Although these aquatic product heavy metal testing data from source countries cover 60.2 % of global aquatic food consumption, many countries in Africa and Southeast Asia lack data. We used global average heavy metal concentrations for different aquatic species categories rather than country-specific data to standardize risk comparisons across different countries and regions. This approach may have simplified differences between countries and regions—for example, environmental heavy metal concentrations differ between Northern and Southern Europe, and developing countries have weaker pollution control and may face serious pollution during industrialization and urbanization processes. We recommend that the WHO database and future research supplement data from developing regions. However, even within the same country, the same species from different regions can have varying heavy metal content due to local pollution levels, with these concentration differences primarily determined by trophic level and species category composition (Xiang et al., 2024). We centered our risk assessment and management strategies on the species-specific heavy metal content resulting from biological characteristics, which aligns with species-centered assessment research frameworks for evaluating heavy metal risks in aquatic products from FAO/WHO and FDA (FAO/WHO, 2024; FDA, 2021a).

Our analysis focused on edible parts, but some populations consume the entire fish or animal due to dietary habits and affordability (Beveridge et al., 2013; Newton et al., 2014). Based on physiological mechanisms and animal studies, methylmercury's health effects appear to vary with selenium status and intake, though human research in this area remains limited (FAO/WHO, 2024). Due to the influence of heavy metal bioavailability (the absorption process of heavy metals after entering the body) and bioaccessibility (the release and dissolution process of heavy metals in the digestive tract), the actual risk levels of heavy metals in aquatic products may be lower (Afonso et al., 2015; Bradley et al., 2017; Vicente-Martorell et al., 2009). More assessment is needed in these areas to help governments and food safety agencies develop more scientific standards and regulatory measures.

5. Conclusion

This study presents the first global assessment of heavy metal risks in aquatic foods and provides crucial insights into heavy metal exposure from aquatic foods consumption. While 97.6 % of aquatic food samples comply with safety standards, significant variations in heavy metal concentrations among different species categories highlight the necessity for targeted, species-specific consumption strategies. Trophic level plays a pivotal role in metal accumulation, with fish exhibiting significantly higher mercury levels, molluscs showing elevated cadmium, lead, and arsenic concentrations, and cephalopods displaying high cadmium levels. Mercury is the primary factor causing most fish species to exceed safe exposure limits and present high non-cancer risks, while arsenic and cadmium are the main determinants of safe intake limits and cancer risks for crustaceans, molluscs, and cephalopods.

Many countries exceed health risk thresholds, with varying risk sources and levels. While safe consumption limits are above current global average consumption level, restricting high-risk species consumption would better reduce health risk levels. This study provides a comprehensive framework for understanding heavy metal risks, offering valuable guidance for developing targeted dietary guidelines and public health policies.

6. Methods

6.1. Data sources

In this study, we collected test records for four significant heavy metals—mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As)—present in the edible portion of aquatic foods from the Food Safety Collaborative Platform (FOSCOLLAB) published by the WHO (WHO, 2020b, 2018a). The FOSCOLLAB database is a comprehensive global database that integrates multiple reliable databases from different sources: the JECFA (Joint FAO/WHO Expert Committee on Food Additives) database, the JMPR (Joint FAO/WHO Meeting on Pesticide Residues) database, the GEMS/Food Contaminants (Global Environment Monitoring System for Food Contamination) database, the FAO/WHO Chronic individual food consumption database (CIFOCOss), the WHO Collaborating Centers Database, and data from other UN organisations.

The database is collected by the Global Environment Monitoring System – Food Contamination Monitoring and Assessment Programme. Due to the integration of multiple databases under WHO/FAO, the FOSCOLLAB database does not provide detailed descriptions of analytical methods for individual samples or specify the handling of detection and quantification limits. However, the vast majority of data originates from certified laboratories, and WHO has implemented all reasonable precautions to verify data quality (WHO, 2018b). The database demonstrates key strengths including large sample sizes, broad geographic coverage, ethical transparency, and compliance with international data governance standards, establishing it as a valuable resource for evidence-based research (Marvin et al., 2017).

In heavy metal contamination in aquatic food research, experimental studies typically involve a few dozens to a few hundred samples, conventional *meta*-analyses typically rely on up to a few thousand samples, and our study leverages 138,281 records from the WHO database. The detection data is sourced from records of 39 countries and regions, including EU member states, China, the United States, and Japan, these countries collectively represented 60.2 % of global aquatic food consumption in 2019 (FAO, 2024a). This unprecedented breadth offers unparalleled statistical power and generalizability that individual experimental studies or conventional *meta*-analysis, with limited sample sizes cannot achieve (Cai et al., 2025; Chen et al., 2025; Xiang et al., 2024).

Our research focuses on mercury, cadmium, lead, and arsenic, as these are widely recognized as the most hazardous to human health, particularly through dietary exposure. The WHO identifies mercury, cadmium, lead, and arsenic as the only four metals among its '10 chemicals of major public health concern. Methylmercury (MeHg) is the primary toxic form of mercury found in aquatic food. Mercury in aquatic food exists mainly in the form of methylmercury, and total mercury content is typically used as a proxy indicator for methylmercury (FAO/WHO, 2024). In the FOSCOLLAB database, mercury contamination is primarily reported as total mercury, which is also the reporting format used in most current research. Chen et al. 2025 (Chen et al., 2025) pioneered the establishment of linear correlation conversion rates from total mercury (THg) to MeHg based on trophic levels: 0.93 for high trophic levels (TL 4–5), 0.96 for medium trophic levels (TL 3–4), and 0.45 for low trophic levels (TL 2–3). However, the range between trophic levels 2–3 remains relatively broad, potentially non-linear, and relies on limited data, requiring more data and future research for verification. This conversion rate primarily transforms the methylmercury content of low-trophic-level molluscs. Considering that mercury is higher in medium and high trophic level fish than in lower mercury content molluscs with less supply and edible portions (Zhang et al., 2022b; FAO/WHO, 2024), this conversion rate does not significantly impact risk assessment (Chen et al., 2025). Therefore, to reduce uncertainty, this study uniformly identifies total mercury and methylmercury as methylmercury for assessment purposes, which is consistent with previous risk assessment studies (Afonso et al., 2015; Djedjibegovic et al., 2020) and is both reasonable and practical.

Moreover, 'arsenic' refers specifically to inorganic arsenic, as arsenic in aquatic foods is primarily found in its less toxic organic form (WHO, 2022), and total arsenic measurement does not distinguish between the toxicities of various arsenic forms present (Sharma and Sohn, 2009). Regulatory bodies and health organisations worldwide are primarily concerned with reducing exposure to inorganic arsenic (ATSDR, 2023). It is worth noting that scientific debate continues regarding the exact definition of the term “heavy metals” (Ali and Khan, 2018). For example, the International Union of Pure and Applied Chemistry (IUPAC) does not recognize the term “heavy metals,” and arsenic is technically a metalloid (Duffus, 2002). However, in the context of environmental toxicology, public health, and policy, mercury, cadmium, lead, and arsenic are commonly referred to as heavy metals (Järup, 2003; Milenkovic et al., 2019; Wei et al., 2023), and their toxicological effects on human health have been well documented. Our research aims to provide information to the scientific and public health communities, where “heavy metals” is the more widely accepted term for these environmental pollutants and is extensively used in environmental studies (Tchounwou et al., 2012).

While other metals, such as zinc, silver, and chromium, may have health implications, they are not primarily associated with significant dietary risks through aquatic food consumption. While zinc is an essential trace element required for human health, it can cause toxicity in excessive amounts. However, the primary health risks associated with zinc are typically not related to dietary exposure from aquatic foods, but rather from overexposure in industrial settings or from supplementation (Roney, 2005). Similar to zinc, silver is a metal of concern in certain specific contexts, such as in the use of silver nanoparticles in medical and industrial applications. Dietary exposure to silver through aquatic foods is not typically associated with significant health risks (Kuempel et al., 2021). Chromium, particularly hexavalent chromium (Cr-VI), is recognized for its carcinogenic properties, especially through industrial exposure (Oginawati et al., 2021). However, dietary exposure to Cr-VI through aquatic foods is considered minimal. This is because chromium in aquatic ecosystems is typically found in the less toxic trivalent form (Cr-III), which is not only non-carcinogenic, but also an essential nutrient required in trace amounts for normal human metabolism (Trumbo et al., 2001). Furthermore, Cr-VI is readily transformed to Cr-III when absorbed by fish, significantly reducing its potential to cause harm (Aslam and Yousafzai, 2017).

We obtained average EPA and DHA data for different aquatic species from the Report of the Joint FAO/WHO Expert Consultation on the Risks and Benefits of Fish Consumption (FAO/WHO, 2011). These data primarily came from national aquatic food composition databases provided by France, Japan, Norway, and the United States, as well as a published international database, which is recognized by aquatic food experts for its data quality.

We collected the Maximum Residue Levels (MRLs) of contaminants from national and regional food safety standards to evaluate qualification ratios of aquatic foods (NHFPC and NMPA, 2017; The European Commission, 2023). Food safety standards in the EU are generally stricter than those in other major aquatic food consumption countries such as the USA and China (Guo et al., 2023). We adopted the MRLs of mercury, cadmium, and lead set by the EU to achieve a more rigorous assessment (Djedjibegovic et al., 2020; The European Commission, 2023). Due to the lack of food safety standards for arsenic from the EU, we adopted the MRLs of arsenic set by China (NHFPC and NMPA, 2017).

We sourced information on aquatic species traits and taxonomy, including habitat, climate zone, type of water, feeding path, body shape, max depth, maximum length (Lmax), trophic level, resilience, fishing vulnerability score, K (growth coefficient), and age at first maturity (tm) (Supplementary Table 8), from three key online databases: Fishbase, Sealifebase, and Sea Around Us (Froese and Pauly, 2023; Palomares and Pauly, 2023; Pauly et al., 2020). Many of these traits and taxonomy parameters have been found to be important factors related to nutritional value and micronutrient concentrations of aquatic foods in previous studies (Golden et al., 2021; Hicks et al., 2019). The detailed data provided by these platforms offered invaluable insights into the biological and ecological characteristics of the species under study, facilitating a nuanced analysis of potential variations in heavy metal accumulation across different taxonomic groups.

Although the FAO food balance database provides data updated to 2022 (FAO, 2024c), we chose to collect the latest data on apparent consumption for 2019 from the FAO Fisheries and Aquaculture Department statistical database FishStatJ (FAO, 2024a). This choice was made because many countries did not report accurate data during the pandemic period, whereas the 2019 data from FishStatJ, which predates the COVID-19 pandemic outbreak, would not have significant impacts on data quality and can reflect actual consumption patterns (Chen et al., 2025; Love et al., 2021a). Additionally, the FishStatJ database provides more complete country data than what is available in the FAO food balance database. Furthermore, we obtained global population data for 2019 from the official database of the United Nations (UN DESA, 2022), facilitating our assessment of per capita aquatic food consumption and the associated risks of heavy metal exposure. The FAO database lists 235 countries and regions; however, consumption data are only available for 224. Therefore, our analysis of food safety risks related to heavy metal intake was limited to these 224 countries and regions.

We sourced economic factors, specifically per capita GDP data, from the World Bank (World Bank, 2022), and geographical factors, such as country area and coastline length, from the Central Intelligence Agency (CIA, 2022). These metrics were instrumental in examining the influence of economic status and geographical variables on heavy metal risk levels.

6.2. Data cleaning and management

We managed all the data in Excel (Microsoft, 2022), employing a multi-step data-cleaning process that included data normalisation, outlier detection, and manual validation of species names against authoritative databases. We aligned the aquatic foods reported in the FOSCOLLAB database with the International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) adopted by the FAO (FAO, 2024a), and compared the list of scientific names from the ISSCAAP species against those in FishBase (Froese and Pauly, 2023) and SealifeBase (Palomares and Pauly, 2023) to identify valid scientific names and resolve any discrepancies or synonyms. We then categorised all species into four aggregate categories: cephalopods, molluscs (excluding cephalopods), crustaceans, and fish. We further divided the fish category into four subcategories: demersal marine fish, pelagic marine fish, other marine fish, and freshwater fish (Supplementary Table 9). These species categories and subcategories align with the species groups adopted by the FAO (FAO, 2024a). We used the average values of EPA and DHA data for aquatic product species, along with the production volume of aquatic products as weights, to calculate the average values of EPA and DHA data for different aquatic species categories.

WHO's data on aquatic products is primarily reported on a wet weight basis, except for dried fish. Dried fish, reported on a dry weight basis, represents only 0.076 % (n = 106) of the total dataset. However, due to the small proportion of dried fish in the dataset, lack of species information for dried fish, difficulty in generating meaningful results, and the absence of a reliable method to convert or compare metal concentrations between wet and dry weights, we have excluded these data points from the analysis.

As food safety test results in FOSCOLLAB are based on the edible portion of food (WHO, 2020b, 2019), we converted apparent consumption data into edible food equivalents consumption data using the subsequent conversion factors: for fish, a factor of 1.15 was used, considering it gutted with the head-on; for crustaceans, a factor of 2.80 was applied, referencing tail meat that has been peeled; for cephalopod, a factor of 1.44 was applied, referencing tail meat that has been peeled; and for molluscs, a factor of 6.0 was used, representing meat (Edwards et al., 2019; Tacon and Metian, 2013). Using these factors involves making some assumptions and simplifications, which might not fully capture all the intricacies of processing methods, product forms, or the specific differences in edible portions among species. However, these conversion factors are well-established in the literature and offer a practical and widely accepted approach for estimating edible portions (Naylor et al., 2021; Zhang et al., 2022b). Using these edible food equivalent consumption data and population data, we determined per capita daily apparent consumption metrics for aquatic foods globally and nationally.

In the Methodology section of the WHO Global Environment Monitoring System (GEMS) / Food Contamination Monitoring and Assessment Programme's 'Dietary Exposure Assessment of Chemicals in Food,' the description of 'Concentration data for estimating chronic dietary exposure' is as follows (WHO, 2020b): Summary statistics, such as the mean, may be derived from the concentration data set for each food or food group for use in a deterministic estimate of chronic dietary exposure. In some cases, the distribution of concentration data may be highly skewed to the right-hand side by a small proportion of high values or outliers, where the mean is considerably higher than the median value. Options available as alternatives to using the arithmetic mean include 1) using the median concentration, particularly for chemicals where there are few data points, 2) trimming the distribution to remove outlier values when they are considered to not represent the levels to which people are likely to be exposed, then calculating the arithmetic mean value, or 3) using an alternative method to define the central tendency measure, which reduces the impact of a small number of very high concentration values.

Following WHO methodological guidance, we calculated the mean and median values of heavy metal content in aquatic foods and found that the data showed a right-skewed distribution, with the mean being much higher than the median. We used a 5 % two-sided trimmed mean to replace the arithmetic mean in order to reduce the impact of high values or outliers on the calculation of central tendency indicators (Huang et al., 2019; Wilcox, 2011). Additionally, to avoid the hidden risk of underestimating true exposure that the trimmed mean might introduce, we used bootstrap (1,000 resampling iterations, independent of normality assumptions) to estimate the sampling distribution of heavy metal concentrations (Dixon, 2006), and took its 97.5th percentile as the upper 95 % confidence interval to provide a conservative upper limit for exposure levels.

To compare the distributions of heavy metal concentrations across different aquatic food categories, we conducted the two-sided non-parametric Kolmogorov-Smirnov (KS) test for independent samples in SPSS statistical software (version 26, IBM 2023). The KS test is a widely used non-parametric method for comparing the cumulative distribution functions of two or more independent samples without making assumptions about the underlying distribution of the data (Kvam et al., 2022). This test is beneficial for analysing heavy metal data, which often exhibits non-normal and skewed distributions.

To minimise the impact of potential outliers on health risk evaluations, we also derived another set of average values by excluding the lowest and highest 5 % of data points (Wilcox, 2011) using R. This approach, known as trimmed means, is a robust statistical method that mitigates the influence of extreme values on calculating central tendency measures. While trimmed means can introduce bias in cases where the data distribution is heavily skewed or contains outliers on both sides, the heavy metal data in our study exhibited a predominant skewness towards higher values, making trimmed means a suitable choice for reducing the impact of potential outliers at the high end of the distribution.

We used this trimmed dataset and trimmed mean values for analysing the influence of environmental and ecological traits on heavy metal accumulation in aquatic species, heavy metal intake, health risk evaluations, and recommended daily maximum intake calculations, providing a more conservative and reliable estimate of central tendency. In contrast, we used non-trimmed data to present heavy metal concentrations in global aquatic foods, perform Monte Carlo analysis, and assess the compliance of these foods with heavy metal safety standards. This approach allowed us to capture the full variance and uncertainty of the data.

6.3. *Two-factor analysis of species and geographic variability*

Data containing four heavy metal detection values (Value), aquatic product species (Species), and detection countries (Country) were extracted from the dataset, and the aquatic product species and detection countries were properly converted into factor types. A two-way analysis of variance (ANOVA) model was employed to analyze the significant effects of aquatic product species, detection countries, and their interactions on heavy metal content. Following the ANOVA, p-values for each factor were extracted for statistical inference, and the sum of squares from the ANOVA results was used to calculate the contribution percentages of main effects and interactions to the variation in heavy metal content, ensuring that the total contribution summed to 100 %. The relative contribution rates of main effects and interactions to response variable variation were visualized using Venn diagrams for overlap representation and bar charts for comparative analysis.

6.4. *Assessment of heavy metal levels relative to safety standards*

To ascertain the concentration levels in different food commodities against food safety standards (Supplementary Table 1), we calculated compliance rate as follows:

$$Compliance\ rate = \frac{Number\ of\ qualified\ samples}{Total\ number\ of\ samples} \times 100\% \tag{1}$$

We compared all reported values with the MRLs set in food safety standards. We labelled samples with contaminant concentrations exceeding these levels as 'failed, ' while those below the levels as 'qualified.' Given the potential for uneven sampling in testing different species categories, we used the edible production of each aquatic food as a weighting factor to determine the overall qualification ratios of total global aquatic foods. We excluded unspecified species due to inconsistency standards.

6.5. Environmental and ecological traits and heavy metal accumulation analysis

We used Random Forest regression models to explore the relationship between heavy metal contaminant levels (trimmed mean values) and aquatic species traits and taxonomy. Random Forest is a powerful machine learning technique that constructs multiple decision trees during training, utilising bootstrap sampling and random feature selection (Qi, 2012). This ensemble learning approach addresses the overfitting issues common in single decision trees by averaging or aggregating the results, offering a robust solution for analysing non-linear relationships and determining feature importance (Fawagreh et al., 2014). The ability to capture non-linear relationships and determine feature importance made Random Forest particularly well-suited for our analysis, as the accumulation of heavy metals in aquatic organisms is likely influenced by complex interactions between various environmental and ecological traits.

We addressed missing environmental and ecological traits and concentrations of four heavy metals (Mercury, Cadmium, Lead, and Arsenic) in the dataset by employing a hierarchical imputation method based on taxonomy. Recognising the structured nature of biological classification, the imputation utilised the most frequent value (mode) for categorical variables in environmental and ecological traits, median values for numerical variables in environmental and ecological traits, and the concentrations of four heavy metals from the most specific available taxonomic level (Genus, Family, Order, Class, Phylum) in descending order of specificity. This strategy was chosen to maintain ecological and biological relevancy, with median values ensuring robustness against potential outliers, thereby enhancing the reliability of our environmental assessments.

We trained a Random Forest model using the preprocessed features for each target variable (the concentration of mercury, cadmium, lead, and arsenic). We used the RandomForestRegressor implementation from the RandomForest package in R. The random forest model splits the dataset into a training set and a test set in a 70 %:30 % ratio and uses the ntree (number of trees) parameter value of 500 and defaults for other parameters. We conducted the training process with a fixed seed at 123 to ensure reproducibility. We extracted the explanatory power of the predictors using the Increase in MSE (%) metric, which calculates the relative importance of each predictor. Increase in MSE (%) represents the percentage increase in model error when each predictor is permuted; a higher value indicates a greater impact of that predictor on the model's predictions. This provides valuable insights into which environmental or biological traits most strongly influence heavy metal concentrations in aquatic organisms.

We implemented Random Forest models using two configurations. The first configuration applied to all aquatic species in the model's four categories (cephalopods, other molluscs, crustaceans, and fish), excluding the 'Body shape' parameter. Conversely, the second configuration was tailored specifically for finfish species (fish category), integrating the 'Body shape' parameter. In the initial stages of data preprocessing, we addressed missing values and encoded categorical variables through one-hot encoding. We processed categorical variables using label encoding.

Following this, we harnessed the feature importance derived from the Random Forest models to discern the most pivotal features associated with each contaminant. To emphasise overarching factors, we aggregated importance by factor categories. We then visualised their aggregated importance to ascertain their relative significance. Further, we conducted a correlation analysis to understand the relationships among the different variables in our dataset. We elucidated the interrelation between these broader factors and the contaminants using correlation heatmaps. Pearson correlation coefficients and associated p-values were calculated using the corr.test function from the psych package in R. The Pearson method was specified to compute the linear correlation between the heavy metal levels and each species' environmental and ecological traits. We evaluated the performance of Random Forest models using several metrics, including the Mean Absolute Error (MAE), the Root Mean Square Error (RMSE), and the Coefficient of Determination (R^2).

6.6. Health risk assessment

To assess the potential health risks associated with ingesting heavy metals from aquatic foods at both global and national levels, we conducted three types of evaluations: exposure risk, non-cancer risk, and cancer risk, using trimmed mean values of heavy metals. We analysed these using the indicators Estimated Daily Intake (EDI) for exposure risk, Targeted Hazard Quotient (THQ) and Hazard Index (HI) for non-cancer risk, and Carcinogenic Risks (CR) for cancer risk.

The EDI is a commonly used metric to determine the daily intake of individual metals in the oral exposure route (Supplementary Table 10). We calculated the EDI of each analysed heavy metal using the method outlined by (Djedjibegovic et al., 2020; Rakib et al., 2021; Saha et al., 2016), which is consistent with the guidelines provided by the United States Environmental Protection Agency (EPA, 2000):

$$EDI = \frac{E_F \times E_D \times FIR \times C_m}{W_{AB} \times T_A} \times 10^{-3} \tag{2}$$

where: EF = exposure frequency (365 days $year^{-1}$); ED = exposure duration (70 years), equivalent to average lifespan; FIR = aquatic food ingestion rate (g $person^{-1}$ day^{-1}) calculated based on apparent consumption; C_m = metal concentration (mg kg^{-1}); W_{AB} = average body weight (kg) 70 kg for adults; T_A = average exposure time for non-carcinogens (365 days $year^{-1}$ x ED).

The THQ indicates potential non-cancer health risks stemming from ingesting specific chemical elements (Djedjibegovic et al., 2020; Rakib et al., 2021; Saha et al., 2016; USEPA, 2000). THQ represents the ratio of the exposure level to a particular substance over a specific period of time to the Reference Dose (RfD) of that particular substance (Djedjibegovic et al., 2020; EPA, 2000; Saha et al., 2016; USEPA, 2000). We calculated the THQ value using the following formula (Djedjibegovic et al., 2020; Saha et al., 2016; USEPA, 2000):

$$THQ = \frac{E_F \times E_D \times FIR \times C_m}{W_{AB} \times T_A \times RfD} \times 10^{-3} = \frac{EDI}{RfD} \tag{3}$$

To assess the potential risk of adverse health effects from mixtures of toxic metals, we calculated the HI (Djedjibegovic et al., 2020; Rakib et al., 2021). An HI value greater than one generally indicates a potential adverse effect on human health and suggests the need for further investigation or possible remedial action.

$$HI = THQ_{Hg} + THQ_{Cd} + THQ_{Pb} + THQ_{As} \tag{4}$$

CR refers to the increased probability of an individual developing cancer over their lifetime due to exposure to potential carcinogens. Using the Cancer Slope Factor (CSF) published by EPA, we calculated the cancer risk of lifetime exposure to the heavy metals cadmium, lead and arsenic using the following formula (Rakib et al., 2021; Saha et al., 2016; USEPA, 2000). We excluded mercury from the analysis because it lacks a cancer slope factor.

$$CR = \frac{E_F \times E_D \times FIR \times C_m}{W_{AB} \times T_A} \times 10^{-3} \times CSF = EDI \times CSF \tag{5}$$

We explored the potential influence of socio-geographical factors, such as income level, population, geographical area, and coastline length, on heavy metal intake risks. We further derived the following metrics and included them in the analysis: the ratio of coastline length to the country area (km km^{-2}), the ratio of coastline length to population (km $million^{-1}$), and the ratio of population to the area (million km^{-2}). We used Random Forest regression models to analyse the correlation between socio-geographical factors and heavy metal intake risks, following the methodology outlined in the previous section. We specifically analysed heavy metal intake from consuming aquatic foods in six key aquatic food-consuming countries and regions: the EU, China, the UK, the USA, India, and the ASEAN. The rationale for selecting these countries and regions includes their large populations (such as India and China), their status as major consumers and importers of aquatic foods (such as the EU and the USA), or their extensive coastlines (such as the UK and ASEAN).

6.7. Risk-benefit assessment

The FAO/WHO Joint Expert Committee Report on the Risks and Benefits of Fish Consumption established an analytical framework for assessing the net health benefits/risks of aquatic food consumption (FAO/WHO, 2011). Following the guidance of the report's analytical framework, we evaluated deaths prevented per million people due to intake of EPA + DHA from aquatic food consumption (Eq. (6)), and referencing the formula for cancer deaths per million people caused by intake of dioxins/DL-PCBs as well as the corresponding cancer slope factors for heavy metals (Supplementary Table 10), we derived the formula for cancer deaths caused by heavy metals intake (Eq. (7)). Combining Eqs. (6) and (7) gives an equation of net mortality change and consumption of aquatic foods due to intake of EPA + DHA and heavy metals.

$$\textit{Deaths prevented per million people} = \frac{[EPA + DHA] \times 100 \times \frac{x}{7}}{250} \times 0.36 \times D \tag{6}$$

where: [EPA + DHA] is the total concentration of EPA plus DHA in aquatic food (mg/g); 100 is the estimated fish serving size (g); x is the number of servings of fish per week (7 days); 0.36 is the proportional reduction in coronary heart disease deaths, with reduction in deaths assumed to be linearly related to DHA intake up to 250 mg/day, i.e., the maximum value of '[EPA + DHA] × 100×(X/7)' was 250 mg; D is the estimated number of coronary heart disease deaths per million people (1580 deaths per year per million people, calculated over 70 years).

$$\textit{Cancer deaths caused per million people} = [HMs] \times 100 \times \left(\frac{x}{7}\right) \div 70 \times CSF_{HMs} \times 10^{6} \tag{7}$$

where: [HMs] is the concentration of heavy metals in aquatic food (mg/g); 100 is the estimated aquatic food serving size (g); and x is the number of servings of aquatic food per week; FAO/WHO uses a human body weight of 60 kg, while 70 kg was used here to be consistent with the exposure risk assessment section.

$$\textit{Net prevented deaths} = \textit{CVD deaths prevented} - \textit{Cancer deaths caused} \tag{8}$$

As well as intelligence quotient (IQ) points gained due to increased EPA + DHA intake (Eq. (9)) and IQ points lost due to the impact of methylmercury intake on infant neurodevelopment (Equation (10)). Combining Eqs. (9) and (10) gives an equation of net IQ points change and consumption of aquatic foods due to intake of EPA + DHA and methylmercury.

$$\textit{IQ points gained} = [EPA + DHA] \times 100 \times 0.67 \times \left(\frac{x}{7}\right) \times 0.04 \tag{9}$$

where: [EPA + DHA] is the total concentration of EPA plus DHA in aquatic food (mg/g); 100 is the estimated aquatic food serving size (g); 0.67 is the factor used to estimate DHA concentration from [EPA + DHA]; x is the number of servings of aquatic food per week; and 0.04 is the coefficient relating IQ points gained to milligrams of DHA intake per day.

$$\textit{IQ points lost} = [MeHg] \times 100 \times \left(\frac{x}{7}\right) \div 60 \times 9.3 \times (-0.18 \ \textit{or} \ -0.7) \tag{10}$$

where: [MeHg] is the concentration of methylmercury in aquatic food (μg/g); 100 is the estimated aquatic food serving size (g); x is the number of servings of aquatic food per week (7 days); 60 is the estimated maternal body weight (kg); 9.3 is the correlation between maternal methylmercury intake and maternal hair mercury level; −0.18 is the central estimate of IQ points gained per microgram per gram hair mercury gained; and − 0.7 is the upper-bound estimate of IQ points gained per microgram per gram hair mercury gained. In this study, we chose −0.7 as IQ points lost per microgram per gram hair mercury for a more conservative assessment.()

$$\textit{Net IQ points gained} = \textit{IQ points gained} - \textit{IQ points lost} \tag{11}$$

6.8. Recommended daily maximum intake calculation

We use Benefit-Risk Quotient (BRQ_{Deaths} and BRQ_{IQ}) to assess the risk–benefit comparison of aquatic food consumption. If BRQ is less than 1, it indicates that the benefits of consuming the aquatic food outweigh the risks; if BRQ is greater than 1, the risks outweigh the benefits. For aquatic food with a BRQ less than 1, when the daily intake of EPA + DHA reaches 250 mg, the health benefits plateau, forming a maximum benefit threshold, while the risk of pollutant exposure increases. The risk–benefit-based limit (FIR_{Deaths} and FIR_{IQ}) can be calculated when the risk equals the maximum benefit threshold.

$$\begin{aligned} BRQ_{Deaths} &= \frac{\textit{Cancer deaths caused}}{\textit{CVD deaths prevented}} \\ &= \frac{[HMs] \times 100 \times \left(\frac{x}{7}\right) \div 70 \times CSF_{HMs} \times 10^{6}}{\frac{[EPA+DHA] \times 100 \times \frac{x}{7}}{250} \times 0.36 \times D} \end{aligned} \tag{12}$$

$$FIR_{Deaths} \leq \frac{39816 \times 70}{10^{6} \times [HMs] \times CSF_{HMs}} \tag{13}$$

$$BRQ_{IQ} = \frac{\textit{IQ points lost}}{\textit{IQ points gained}} = \frac{[MeHg] \times 100 \times \left(\frac{x}{7}\right) \div 60 \times 9.3 \times 0.7}{[EPA + DHA] \times 100 \times 0.67 \times \left(\frac{x}{7}\right) \times 0.04} \tag{14}$$

$$FIR_{IQ} \leq \frac{5.8 \times 60}{0.7 \times 9.3 \times [MeHg]} \tag{15}$$

We assessed the daily exposure and non-cancer and cancer risk conditions of various aquatic foods based on established risk thresholds (Supplementary Table 10) and determined the risk-based limit.

We adopted reference values (Wong et al., 2022) for EDI: arsenic ≤ 0.0003mg kg^{-1} day^{-1}, cadmium ≤ 0.0001 mg kg^{-1} day^{-1}, lead ≤ 0.00016 mg kg^{-1} day^{-1}, and mercury ≤ 0.00019 mg kg^{-1} day^{-1}. These values are based on guidelines from various authoritative bodies, including the USEPA reference doses and the provisional tolerable intake values set by JECFA (Wong et al., 2022). We adopted the reference values for the Target Hazard Quotient (THQ) and Cancer Risk (CR) as THQ ≤ 1 and CR ≤ 0.00001 (risk of developing cancer over a human lifetime is 1 in 100,000), respectively, to identify potential health hazards from consuming specific foods (Djedjibegovic et al., 2020; Rakib et al., 2021; Saha et al., 2016; USEPA, 2000). Additionally, we adopted a less stringent benchmark (CR ≤ 0.0001) for calculating the recommended maximum daily intake (Wang et al., 2020).

The derivation formula is as follows:

$$FIR_{EDI} \leq \frac{\textit{Reference value} \times W_{AB} \times T_{A} \times 10^{3}}{E_{F} \times E_{D} \times C_{m}} \tag{16}$$

$$FIR_{THQ} \leq \frac{RfD \times W_{AB} \times T_A \times 10^3}{E_F \times E_D \times C_m} \tag{17}$$

$$FIR_{CR} \leq \frac{W_{AB} \times T_A \times 10^{-2}}{E_F \times E_D \times C_m \times CSF} \tag{18}$$

$$Recommended\ maximum\ daily\ intake = \ll FIR_{Deaths}, FIR_{IQ}, FIR_{EDI}, FIR_{THQ}, FIR_{CR} \gg_{min} \tag{19}$$

Our food safety risk analysis was based on the global average consumption of edible aquatic foods at 40 g person^{-1} day^{-1} (Naylor et al., 2021) In line with the FDA's guidelines (FDA, 2022), we classified aquatic foods into three risk categories based on their recommended daily maximum intake: 'Best Choices' for low-risk foods with an intake equal to or higher than 40 g person^{-1} day^{-1}, 'Good Choices' for medium-risk foods with an intake equal to or higher than 20 g person^{-1} day^{-1} but less than 40 g person^{-1} day^{-1}, and 'Limit' for high-risk foods with an intake of less than 20 g person^{-1} day^{-1}. We calculated the weighted average as the overall aquatic food recommended daily maximum intake using the edible production volume of each aquatic food category as a weighting factor.

6.9. Scenarios and Monte Carlo simulations

We developed three scenarios to explore strategies for mitigating health risks from aquatic food consumption: 'Business as Usual' (BAU), 'Only Best', and 'Limit Worst'.

The BAU scenario serves as a baseline and maintains current consumption patterns of all aquatic foods. The 'Only Best' scenario represents an ideal risk reduction strategy, advocating for the exclusive consumption of low-risk aquatic foods classified as 'Best Choices'. Conversely, the 'Limit Worst' scenario offers a more moderate approach, permitting the consumption of both medium-risk 'Good Choices' and low-risk 'Best Choices' aquatic foods while limiting high-risk options. We selected these scenarios to provide a thorough assessment of risk mitigation strategies, ranging from the status quo to incremental improvements and an optimised approach.

We prepared three corresponding datasets for each scenario: the BAU dataset includes all records, the 'Only Best' dataset encompasses only low-risk 'Best Choices' foods, and the 'Limit Worst' dataset comprises records for both medium-risk 'Good Choices' and low-risk 'Best Choices' foods. Using the Batch Fit tool in Oracle Crystal Ball (version 11), we determined the best-fit distributions for heavy metal concentration (Wei et al., 2023) for these datasets. The choice of best-fit distributions was based on goodness-of-fit tests and visual inspection, aiming to capture the inherent variability and potential skewness in the heavy metal data. While these distributions represent the best available approximations, they may not fully represent the underlying data distributions, leading to potential inaccuracies or biases in the simulated results.

In the Monte Carlo simulations, we required country-level aquatic food consumption data, including the average (mean) and information on the data distribution (shape). We used the FAO per capita apparent consumption as each country's average (mean). Due to limited data availability, we used the WHO's descriptive statistics on consumption to simulate the data distribution (shape) for all countries. The WHO has published descriptive statistics on aquatic food consumption by major aquatic food categories for several major aquatic food-consuming countries (WHO, 2018b). We selected these WHO descriptive statistics on freshwater fish (United States, China, and Bangladesh) and marine fish (United States and China) to represent consumption in countries with different economic profiles (Golden et al., 2021), considering these countries cover high-income (United States), upper-middle-income (China), and lower-middle and low-income (Bangladesh) groups, and have considerable sample sizes (n $\geq$ 100). Due to limited data availability, we used China's descriptive statistics on marine foods to represent lower-middle and low-income countries.

Previous literature supports the premise that aquatic food consumption follows a log-normal distribution (Ruffle et al., 1994; Thomsen et al., 2019; Watanabe et al., 2021). The present study also assumed that aquatic food consumption follows a log-normal distribution. Based on the WHO descriptive statistics, the log-normal distribution assumption, and the national average per capita daily consumption of freshwater and marine aquatic foods, we reconstructed the per capita edible daily consumption data distribution parameters of freshwater and marine aquatic foods for each of the 224 countries using R statistical software.

We then simulated the heavy metal intake under each scenario for the 224 countries. We used the best-fit heavy metal distributions and the reconstructed per capita daily consumption data distribution parameters of freshwater and marine aquatic foods in each country, employing the Monte Carlo simulation via Oracle Crystal Ball (version 11). We set the number of Monte Carlo simulation runs to 1,000 for each of the four heavy metal intakes across the 224 countries and the three scenarios, totalling 2,688 Monte Carlo simulations and 2,688,000 runs.

We assessed the likelihood of exceeding predefined health risk benchmarks (e.g., EDI > Reference value, THQ > 1.0, or CR > 0.00001) based on the outcome of these simulations. For each country, heavy metal, and scenario, we determined the fraction of simulation instances that surpassed these risk benchmarks, interpreting this as the proportion of the population at high risk. We found a higher proportion of the population at risk for cancer under the BAU scenario. To address uncertainties in health risk benchmarks for cancer, our methodology incorporated a less stringent benchmark (CR > 0.0001) used by some studies (Wang et al., 2020), ensuring a cautious approach to our risk assessment. The simulations considered each heavy metal category separately, which might not fully capture the intricate interactions and potential synergistic effects in real-world situations. To accommodate potential correlations or interactions among heavy metals, we grouped the simulation runs of the four heavy metals into datasets, obtaining 1,000 datasets for each of the 224 countries across the three scenarios, resulting in a total of 672,000 datasets. We deemed a dataset to represent a high risk if one or more heavy metals and their associated risks surpassed the specified risk benchmarks. Subsequently, we assessed the overall EDI, non-cancer, and cancer risks using these grouped datasets.

Finally, we calculated the global proportion of the population at high risk across each heavy metal and scenario and the overall proportion of the population at high risk based on four heavy metals grouped datasets, utilising population numbers as weighting factors.

Code availability

The data processing is conducted in Microsoft Excel 2022, R (v.4.3) and SPSS (v.26). All R code used in this study are publicly available on GitHub (https://github.com/AquacultureFuture/HeavyMetalInAquaticFoods).

Author statement

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CRediT authorship contribution statement

Hao Xu: Writing – original draft, Visualization, Software, Methodology, Data curation, Conceptualization. **Richard Newton:** Writing – review & editing, Conceptualization. **David C. Love:** Writing – review & editing, Conceptualization. **Yong Zhao:** Writing – review & editing. **Jogeir Toppe:** Writing – review & editing. **Wenbo Zhang:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

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Author contributions

H.X. and W.Z. conceived the idea and designed the study. H.X. and W.Z. collected and analysed the data. H.X., R.N., D.L., Y.Z., J.T., and W.Z. wrote the paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109831.

Data availability

The heavy metals data are available from the Food Safety Collaborative Platform (FOSCOLLAB), as published by the World Health Organization (WHO, 2018a). The information on aquatic species environmental and ecological traits and taxonomy are available from three online databases: Fishbase, Sealifebase, and Sea Around Us (Froese and Pauly, 2023; Palomares and Pauly, 2023; Pauly et al., 2020). The aquatic food production and apparent data are available from the FAO's FishStatJ database (FAO, 2024a). The aquatic foods EPA + DHA data are available from the report of the joint FAO/WHO expert consultation on the risks and benefits of fish consumption (FAO/WHO, 2011). The global population data are available from the official database of the United Nations (UN DESA, 2022). The per capita GDP data are available from the World Bank (World Bank, 2022), and geographical factors, such as country area and coastline length are available from the Central Intelligence Agency (CIA, 2022). All data analysed in this study and R code are available on GitHub (https://github.com/AquacultureFuture/HeavyMetalInAquaticFoods). Source data are provided with this paper.

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Glossary (Acronyms and definitions)

Hg (MeHg): Mercury (Methylmercury)
Cd: Cadmium
Pb: Lead
As (iAs): Arsenic (Inorganic arsenic)
FAO: Food and Agriculture Organization of the United Nations
WHO: World Health Organization
FDA: United States Food and Drug Administration
THQ: Targeted hazard quotient
CR: Carcinogenic risk

HI: Hazard index
EDI: Estimated daily intake
IQ: Intelligence quotient
MRL: Maximum residue level
CVD: Cardiovascular disease
EPA: Eicosapentaenoic acid
DHA: Eocosahexaenoic acid
Trophic transfer: Movement of a contaminant through food chains from one trophic level to another.
Bioconcentration: Accumulation of a contaminant in an organism from the ambient abiotic environment (water/sediments).
Dietary accumulation: Accumulation of a contaminant in an organism from its food/diet.
Bioaccumulation: Accumulation of a contaminant in an organism from both the ambient abiotic environment and its food/diet.
Biomagnification: Increase in contaminant concentration as it moves up the food chain.
Biodilution: Decrease in contaminant concentration as it moves up the food chain.
Uptake rate: The speed at which an organism absorbs a substance.
Assimilation efficiency: The percentage of a substance that is absorbed and used by an organism.
Efflux rate: The speed at which an organism eliminates a substance.
Bioaccessibility: The fraction of a substance that is released from the food matrix during gastrointestinal digestion and becomes available for absorption.
Bioavailability: The proportion of an administered substance that is absorbed and reaches systemic circulation
Demersal Pelagic: The type of aquatic organism's habitat is distributed in nature.
Climate Zone: The climate zone. Including Subtropical, Tropical, Temperate, and Cold (Polar, deep water, boreal).
Marine Freshwater: The type of aquatic environment in which an organism lives.
Feeding Path: The feeding pathways of benthic or pelagic aquatic organisms.
Body Shape: The body shape of fish.
Depth Range Deep: The deepest depth range in water bodies was reported for juveniles and adults.
Lmax: The maximum length ever reported for the aquatic species.
Trophic Level: The position an organism occupies in a food chain, based on its feeding relationships.
Resilience: Resilience to fishing pressure.
Fishing vulnerability score: A metric used to assess the susceptibility of aquatic species or ecosystems to the impacts of fishing activities.
Growth coefficient: A parameter that quantifies the rate at which an organism increases in size, weight, or other attributes over time.
Age at first maturity: The age at which an organism becomes capable of reproduction for the first time.