JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(5), 407–419
https://doi.org/10.12911/22998993/216125
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.12.12
Accepted: 2026.03.16
Published: 2026.04.01

Seafood safety at stake: Heavy metal bioaccumulation and health risks in yellowfin tuna from Bali's Benoa Bay

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ABSTRACT

The growing global demand for tuna has raised concerns over heavy metal contamination, as these apex predators can bioaccumulate toxic elements through the marine food web. Chronic exposure to lead (Pb), cadmium (Cd), and mercury (Hg) via seafood consumption poses potential public health risks, particularly for sensitive groups such as children and women of reproductive age. This study quantified Pb, Cd, and Hg concentrations in fresh and frozen yellowfin tuna (*Thunnus albacares*) over five years and evaluated non-carcinogenic risks using target hazard quotient (THQ) and total target hazard quotient (TTHQ) metrics. Risk estimates were calculated for children (2–5 years and 6–11 years) and women under both average and high-consumption scenarios. Results indicated that Pb and Cd contributed minimally to overall risk, whereas Hg consistently dominated the THQ profile. For most scenarios, THQ and TTHQ values remained below the United States Environmental Protection Agency's safety threshold of 1.0; however, exceedances were observed in some years for women with high consumption levels. Comparison with global datasets showed that heavy metal concentrations in Benoa Bay tuna were generally lower or comparable to those in other regions of concern, yet still within the worldwide range reported for tuna and other seafood products. These findings highlight the importance of continued monitoring, particularly in areas influenced by urbanization and industrial activities, alongside risk communication strategies and integration of seafood safety into national food policies. Such measures are critical to safeguard public health while advancing sustainable development goal (SDG) 14.

Keywords: bioaccumulation, marine pollution, target hazard quotient, food security, risk assessment.

INTRODUCTION

Seafood is an important source of essential nutrients, providing protein, vitamins A and E, minerals, and omega-3 fatty acids, while at the same time supporting the livelihoods of millions of people, particularly in coastal communities (Abarshi et al., 2017). Across the world, seafood has long been consumed in diverse forms such as fish, mollusks, crustaceans, and shellfish, making it a fundamental component of diets and cultures (Pan et al., 2022; Ralston et al., 2019; Watiniasih et al., 2023). In Indonesia, as a tropical archipelagic country, seafood plays a central role in food security and local economies. Patterns of seafood consumption are shaped by multiple factors, including geographic location, cultural practices, age, gender, and health conditions (Ferreira et al., 2023). Coastal populations typically consume up to 15 times more seafood than those living in inland or urban areas (Pupavac et al., 2022).

Indonesia is also a major contributor to global seafood production. The Food and Agriculture Organization (FAO) projects that aquatic food production will increase by 15% by 2030 globally, with 157 million tons harvested for human consumption in 2020 alone (FAO, 2022). Among marine fish, tuna, particularly yellowfin tuna (*Thunnus albacares*), holds high economic and nutritional value. In 2018, global tuna catches exceeded 7.9 million tons, with yellowfin tuna contributing more than 60% of the total (Vázquez et al., 2022). Indonesia exports large volumes of yellowfin tuna, primarily harvested from the Indian and Pacific Oceans and landed at several ports, including Benoa Harbor in Bali, which serves as a major hub for tuna and other species like skipjack, albacore, cephalopods, and demersal fish (Oktariani et al., 2023; Wiradana et al., 2024; Sudaryatma et al., 2025).

Despite its value, seafood is increasingly threatened by pollution. Coastal development, industrial activity, urbanization, and tourism all contribute contaminants to marine ecosystems (Umeoguaju et al., 2023). Among these pollutants, heavy metals such as lead (Pb), cadmium (Cd), and mercury (Hg) are of particular concern due to their toxicity, persistence, and ability to bioaccumulate in aquatic organisms (Castro-González and Méndez-Armenta, 2008). Consumption of contaminated fish poses serious risk to human health, lead and cadmium exposure has been associated with impaired nervous system function, cardiovascular disease, and reproductive disorders (Genchi et al., 2020; Tamele and Vázquez Loureiro, 2020), while mercury is especially harmful to children, affecting neurological and immune development (Guzzi et al., 2021).

As a top predator, large fish such as yellowfin tuna often accumulate heavy metals over time, making them effective bioindicators for assessing long-term environmental contamination and assessing potential health risk in different population groups (Briaudeau et al., 2019). Mercury and cadmium concentrations exceeding international safety standards have been reported in yellowfin tuna. For instance, a study in the Indian Ocean near Sri Lanka recorded mercury levels above 1 mg/kg in six samples and cadmium levels above 0.01 mg/kg in two samples (Jinadasa et al., 2019). In contrast, studies from Indonesian waters generally reported levels within acceptable limits, though they highlighted the need for continuous monitoring (Oktariani et al., 2023). Research in Brazil similarly found most seafood to be safe, yet identified one species, Corvina (*Cilus gilberti*), with a target hazard quotient (THQ) greater than 1, suggesting potential health risks (Vázquez et al., 2022).

To date, no study has documented long-term trends in Pb, Cd, and Hg contamination in yellowfin tuna landed at Benoa Harbor, creating a critical gap in understanding whether contamination levels are changing over time and how they may affect public health (Azizi et al., 2018; Wasilah et al., 2021). In this study, we investigated Pb, Cd, and Hg concentrations in the muscle tissue of yellowfin tuna landed at Benoa Harbor from 2017 to 2021, including both fresh and frozen samples. We evaluated temporal trends, compared the results with established safety limits, and discussed potential health risks with a particular focus on vulnerable populations such as women and children (Wang et al., 2022). The findings provide reliable biological data for long-term environmental monitoring and contribute to the development of safe seafood consumption guidelines in Indonesia.

MATERIALS AND METHODS

Study area and sample collection

Benoa Harbor, located in the southern part of Bali Province, was chosen as the study site because it is the largest fishing port in the region and an important landing center for yellowfin tuna, which is of concern for heavy metal contamination (Suteja et al., 2021). Sampling locations were situated within Benoa Bay, bordered by Denpasar to the north and Badung Regency to the south, and surrounded by mangrove forests, land-based and fishing industries, tourism, and coastal infrastructure (Figure 1). Yellowfin tuna were obtained from local fishers operating in Benoa Harbor between 2017 and 2021. Specimens were categorized as fresh or frozen muscle tissue. Each sample was

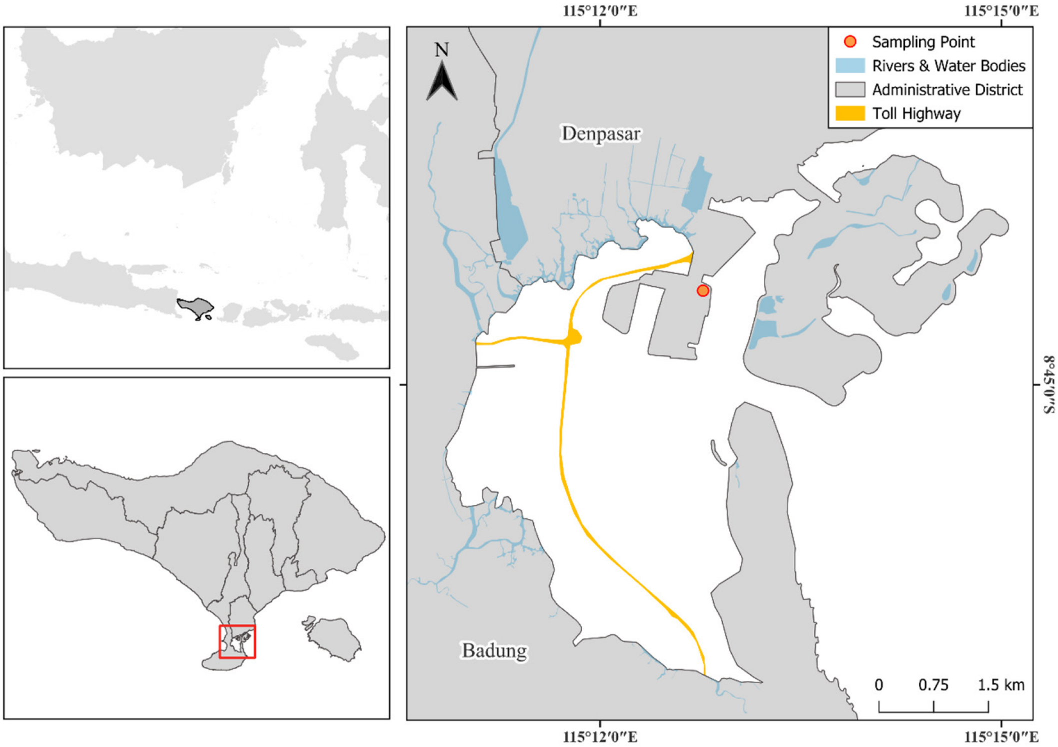

Figure 1. Location of sampling point

placed in sterile zip-lock bags, stored in cooler boxes with ice gel, and transported to the laboratory for processing. In the laboratory, muscle tissues were rinsed with deionized water, dissected, and weighed. Samples were oven-dried to a constant mass, ground into fine powder, and stored in sealed containers for heavy metal analysis.

Heavy metals analysis

Lead and cadmium

Lead (Pb) and cadmium (Cd) concentrations in tuna muscle samples were determined using the official method established by AOAC, (2002). Analyses were conducted with an Atomic Absorption Spectrophotometer (AAS; Shimadzu model AA–6200), equipped with a graphite furnace (GFAAS) and calibrated with appropriate standards. The detection limits using GFAAS were 0.1 mg/kg for Pb and 0.01 mg/kg for Cd. Calibration plots were prepared using Pb standards of 0, 50, 100, and 200 μg and Cd standards of 0, 1, 3, and 5 μg, each diluted in 0.2% HNO_3 solution.

Approximately 0.2–0.5 g of wet muscle tissue was weighed and transferred into a 250 ml Erlenmeyer flask for digestion. A closed-vessel microwave-assisted system was used, with HNO_3 and H_2O_2 added under pressure and heat. After digestion, the vessels were cooled, and the digest was diluted with deionized water prior to analysis. Concentration of Pb and Cd was measured at specific wavelengths of 283.3 nm and 228.8 nm, respectively. To ensure accuracy, calibration reference materials from the International Atomic Energy Agency (IAEA), specifically the IAEA-407 reference product consisting of homogenized fish tissue from pelagic species of the Scombridae family (Ormaza-González et al., 2020).

Mercury

Mercury (Hg) analysis followed the method described by Rahayu et al., (2016). Homogenized muscle tissue was digested in 3 mL of H_2SO_4 and 2 mL of HNO_3 at 80 °C for three hours. Subsequently, 15 mL of $KMnO_4$ solution was added until a stable purple color indicated complete oxidation. A standard calibration curve was prepared using Hg concentrations of 0.0, 2.5, 5.0, and 10 μg [Hg] dm^{-3}, which was then mixed with the sample solution. Excess $KMnO_4$ was neutralized with sodium chloride, and the solution was diluted to 50 mL with deionized water. Mercury concentrations were quantified using a type-IA mercury vaporizer unit connected with the same AAS instrument, operating at a detection wavelength of 253.7 nm.

Health risk assessment

The estimated daily intake (EDI) of heavy metals from the consumption of yellowfin tuna was determined based on the method proposed by Gu et al., (2018), and expressed in mg/kg body weight/day using the following equation:

$$EDI = \frac{IR \times C \times AR}{BW} \quad (1)$$

where: *IR* represents the daily fish intake rate, set at: 16 g/day for children aged 2–5 years, 37.9 g/day for children aged 6–11 years, and 55 g/day and 131.8 g/day for average and high-end consumption scenarios in adult women (Wang et al., 2019). *C* is the concentration of heavy metals in tuna muscle (mg/g wet weight), and *AR* refers to the intestinal absorption rate of contaminants in raw fish muscle.

The absorption rates applied were 35.1% for Pb, 51.9% for Cd, and 15% for Hg (Gu et al., 2018; Wu et al., 2024). Body weights (*BW*) used in the calculations were 59 kg for women, 16.6 kg for children aged 2–5, and 29.8 kg for children aged 6–11.

Non-carcinogenic health risk was assessed using the THQ, which was calculated according to the following formula:

$$THQ = \frac{EDI \times EF \times ED}{RfD \times AT} \times 10^{-3} \quad (2)$$

where: *EF* is the exposure frequency (365 days/year), *ED* is the exposure duration (70 years for women, 3.5 years for children aged 2–5, and 8.5 years for children aged 6–11), *RfD* is the oral reference dose set by the United States Environmental Protection Agency (USEPA, 1997), and *AT* is the averaging time, calculated as 365 days/year multiplied by the number of exposure years.

The *RfD* values used were 0.004 mg/kg/day for Pb, 0.001 mg/kg/day for Cd, and 0.1 mg/kg/day for Hg.

A THQ value below 1 indicates no significant risk of non-carcinogenic health effects. Values between 1 and 10 suggest a potential risk, depending on the exposure level and population vulnerability, with higher values corresponding to an increased probability of adverse outcomes such as reproductive toxicity, teratogenicity, or hepatic damage (Zheng et al., 2007).

The total target hazard quotient (TTHQ) was obtained as the sum of the individual THQ values of each metal, following the approach described by Hasan et al., (2023):

$$Total\ THQ = THQ\ (Pb) + \\ + THQ(Cd) + THQ(Hg) \quad (3)$$

Statistical analysis

Statistical tests were applied to evaluate differences in heavy metal concentrations between sample types and across years. Data were first tested for normality using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Differences between fresh and frozen samples were evaluated with an independent *t*-test, while temporal variation was assessed using one-way ANOVA, with α = significance threshold of $p \leq 0.05$ was applied. All statistical analyses were carried out using IBM SPSS Statistics version 23.0, and results are presented through tables, figures, and graphs. Graphical visualizations were generated using GraphPad Prism version 8.0.1.

RESULTS

Variation in heavy metal concentration

The analysis of heavy metal concentrations in yellowfin tuna muscle tissue, from both fresh and frozen samples, revealed interannual variation across the 2017–2021 sampling period. Lead concentrations in both fresh and frozen samples showed no significant different in 2017, 2018, 2019, and 202. A clear exception occurred in 2020, when frozen tuna exhibited substantially higher Pb concentration than fresh samples (0.12 ± 0.02 mg/kg, w.w vs. 0.03 ± 0.01 mg/kg, w.w; $p < 0.05$; Figure 2A).

Cadmium concentrations displayed a different pattern. No differences were observed between fresh and frozen samples in 2017 and 2018; however, from 2019 to 2021, frozen tuna consistently contained significantly higher Cd concentrations ($p < 0.05$; Figure 2B). In contrast, mercury concentrations remained remarkably stable across years and product types, with no significant differences detected between fresh and frozen tuna from 2017 to 2021 ($p > 0.05$; Figure

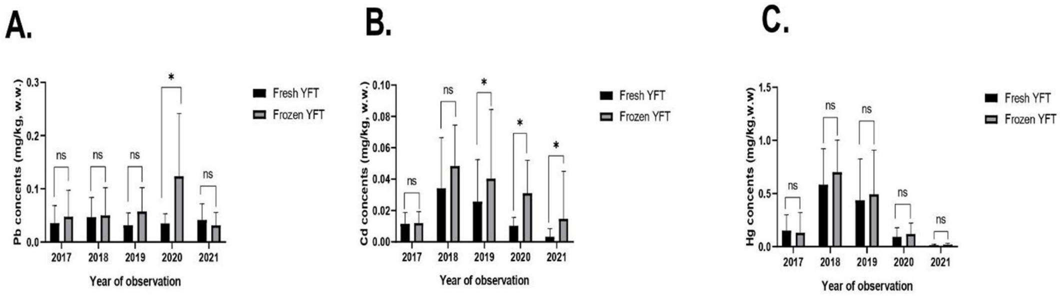

Figure 2. Concentrations of heavy metals Pb, Cd, and Hg in yellowfin tuna (YFT) muscle tissue from fresh and frozen samples landed at Benoa Harbor between 2017 and 2021: (A) lead (Pb) concentrations, (B) cadmium (Cd) concentrations, and (C) mercury (Hg) concentrations. The notation "ns" indicates no significant difference ($p > 0.05$), while "*" denotes a statistically significant difference ($p < 0.05$)

2C). The high mercury accumulation detected in tuna muscle implies this species' susceptibility to the bioaccumulation of this heavy metal. Consequently, regular and stringent monitoring of mercury levels in tuna is a crucial step to ensure food safety for consumers.

Mercury dominates dietary exposure risk

To evaluate potential health risks, the total heavy metal content was used to calculate the estimated daily intake (EDI). Across all years, mercury was the dominant contributor to EDI values, particularly in women under high-consumption scenarios. The highest exposures were observed in 2018 and 2019, when Hg-EDI values in the female population (extreme cases) reached 0.195 (fresh tuna) and 0.235 (frozen tuna), respectively. A gradual decline was observed in subsequent years, with lower exposures estimated for 2021 and 2022 (Figure 3). Even though the EDI value is still considered safe, the population of pregnant women who consume fresh tuna meat has a high risk of accumulation of Hg metals. Furthermore, the highest exposure was found for lead (Pb), primarily observed in the children population (6–11 years old) throughout the 2017–2021 period. This

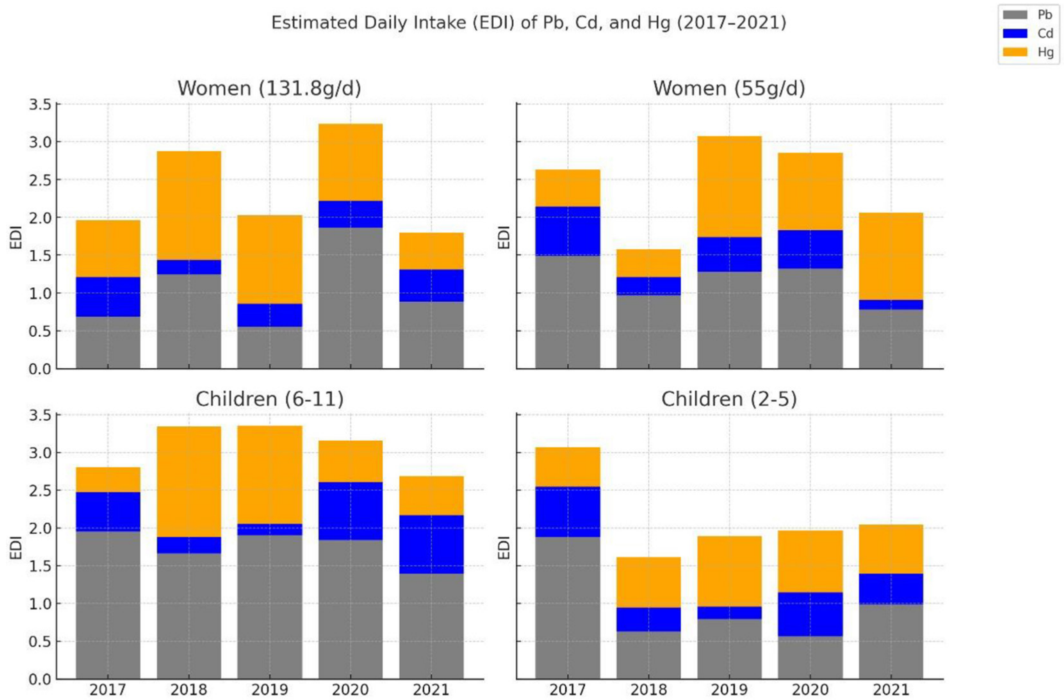

Figure 3. Estimated daily intake (EDI) of heavy metals in yellowfin tuna (fresh and frozen) landed at Benoa Harbor

was followed by exposures in women (131.8 g/d) in 2020, women (55 g/d) in 2017, and the 2–5 years old children population in 2017. Similar to the Estimated Daily Intake (EDI) for mercury (Hg), the EDI values for Pb were still considered within a safe range. However, under this scenario, the 6–11 years old children population exhibits a higher potential risk for Pb accumulation. No significant risk for cadmium (Cd) accumulation was identified under this EDI assessment scenario.

High-consumption scenarios reveal elevated Hg-driven health risk

THQ values varied across metals, years, and population groups. For children aged 2–11 years, values remained consistently very low and well below the non-carcinogenic risk threshold in both fresh and frozen products (Table 1). Among women, normal-consumption scenarios also indicated minimal risk, although frozen tuna tended to present slightly higher THQ values for Pb and Cd in several years. Regardless of product type, Hg was consistently the largest contributor to THQ. Under high-consumption scenarios, THQ values increased markedly, with mercury driving the majority of risk. This trend was particularly evident in frozen samples, where Hg contributed disproportionately to cumulative exposure. Accordingly, TTHQ values, which integrate Pb, Cd, and Hg, followed a similar pattern: while safe levels were maintained for most groups, exceedances were occasionally noted for women under high-consumption conditions, again with frozen tuna showing a slightly higher cumulative burden (Table 1).

DISCUSSION

Heavy metal levels in yellowfin tuna: Local findings and global context

This study showed that concentrations of Pb, Cd, and Hg in yellowfin tuna (*Thunnus albacares*) from Benoa Bay, Bali, were within the maximum permissible limits established by both the Indonesian National Standard (SNI) and the European Union. Despite compliance with these thresholds, risk assessment indicated that the total target hazard quotient (TTHQ) surpassed the safety value of 1 for women under high-consumption scenarios in some years, with mercury emerging as the main contributor.

The accumulation of heavy metals, such as mercury, is accelerated by anthropogenic conditions, including industrial activity, mining, and locations prone to oil spills. Consequently, international health agencies have issued consumption advisories for pregnant women regarding metal-rich fish like tuna (Taylor et al., 2018), a recommendation corroborated by this study's findings on frozen tuna products. Regional comparisons highlight substantial variation in heavy metal levels across tuna fisheries worldwide. In Sri Lanka, a notable proportion of Indian Ocean tuna exceeded Hg limits, while tuna from the Eastern Pacific generally exhibited lower mean concentrations (Jinadasa et al., 2019; Ormaza-González et al., 2020). In Europe, Italian monitoring programs reported higher Hg levels in fresh tuna compared with canned products, and in the Canary Islands, bluefin tuna (*Thunnus thynnus*) frequently surpassed Cd and Pb thresholds. By contrast, studies in other parts of Indonesia and in Pattani Bay, Thailand, found relatively low concentrations of these metals, with minimal health risks to consumers. Research on Spanish-marketed hake and tuna revealed species-specific contamination: arsenic was higher in hake, while mercury was more prevalent in tuna. The study's risk assessment, using Estimated Weekly Intake (EWI) and Allowable Intake Limits, flagged FAO fishing regions 27 and 34 as hotspots for As and Hg, respectively, where consumption may surpass safe levels (Valiente-Diaz et al., 2025). Mercury (Hg) and cadmium (Cd) were the two primary heavy metal contaminants, accounting for 54.9% and 25.8% of all serious notifications, respectively, in global food safety data. Italy was the top notifying country for heavy metals in fishery products, specifically for cadmium (29.0%), mercury (52.6%), chromium (81.0%), and nickel (78.7%). In contrast, China was the most frequently reported country of origin for products containing arsenic (18.7%), cadmium (12.8%), lead (27.6%), chromium (71.2%), and nickel (66.9%) (Eissa et al., 2023).

The results suggest that heavy metal contamination warrants special attention, particularly in pelagic species like yellowfin tuna, due to the ability of these toxins to bioaccumulate in fish tissues and biomagnify within the human food chain (Ray and Vashishth, 2024). The sources of this metal contamination (Pb, Cd, and Hg) include industrial effluent, urban surface runoff, domestic wastewater, as well as mining, smelting, and agricultural practices (Oktariani et al.,

Table 1. THQ value per categories of heavy metal and TTHQ on fresh and frozen yellowfin tuna

Year	Heavy metals	Sample type	Children (2–5 years old)	Children (6–11 years old)	Women (normal cases)	Women (extreme cases)
2017	THQ Pb	Fresh	0.0002	0.0005	0.0033	0.0079
		Frozen	0.0003	0.0008	0.0048	0.0116
	THQ Cd	Fresh	0.0003	0.0009	0.0055	0.0132
		Frozen	0.0003	0.0010	0.0058	0.0139
	THQ Hg	Fresh	0.0109	0.0351	0.2116	0.5071
		Frozen	0.0094	0.0302	0.1825	0.4373
	TTHQ	Fresh	0.0114	0.0365	0.2204	0.5282
		Frozen	0.0100	0.0320	0.1931	0.4628
2018	THQ Pb	Fresh	0.0002	0.0007	0.0044	0.0105
		Frozen	0.0002	0.0008	0.0047	0.0112
	THQ Cd	Fresh	0.0012	0.0038	0.0227	0.0543
		Frozen	0.0013	0.0043	0.0257	0.0617
	THQ Hg	Fresh	0.0421	0.1350	0.8150	1.9529
		Frozen	0.0508	0.1627	0.9821	2.3535
	TTHQ	Fresh	0.0435	0.1395	0.8420	2.0178
		Frozen	0.0523	0.1677	1.0125	2.4264
2019	THQ Pb	Fresh	0.0002	0.0005	0.0029	0.0070
		Frozen	0.0003	0.0009	0.0054	0.0128
	THQ Cd	Fresh	0.0007	0.0022	0.0131	0.0313
		Frozen	0.0012	0.0038	0.0230	0.0552
	THQ Hg	Fresh	0.0316	0.1013	0.6116	1.4655
		Frozen	0.0356	0.1141	0.6889	1.6509
	TTHQ	Fresh	0.0324	0.1040	0.6275	1.5038
		Frozen	0.0371	0.1188	0.7173	1.7190
2020	THQ Pb	Fresh	0.0002	0.0005	0.0033	0.0078
		Frozen	0.0006	0.0019	0.0115	0.0276
	THQ Cd	Fresh	0.0003	0.0008	0.0050	0.0119
		Frozen	0.0008	0.0025	0.0150	0.0359
	THQ Hg	Fresh	0.0068	0.0216	0.1306	0.3131
		Frozen	0.0086	0.0277	0.1671	0.4004
	TTHQ	Fresh	0.0072	0.0230	0.1389	0.3328
		Frozen	0.0100	0.0321	0.1936	0.4640
2021	THQ Pb	Fresh	0.0002	0.0006	0.0039	0.0093
		Frozen	0.0002	0.0005	0.0029	0.0070
	THQ Cd	Fresh	0.0001	0.0003	0.0016	0.0039
		Frozen	0.0001	0.0003	0.0019	0.0046
	THQ Hg	Fresh	0.0010	0.0034	0.0203	0.0486
		Frozen	0.0012	0.0040	0.0241	0.0578
	TTHQ	Fresh	0.0013	0.0043	0.0258	0.0617
		Frozen	0.0015	0.0048	0.0290	0.0694

2023). These comparisons emphasize that health risks associated with seafood consumption are shaped by a combination of geographic origin, species-specific feeding ecology, and product form. Environmental conditions and localized pollution sources strongly influence exposure, explaining why Sri Lankan tuna displayed a greater proportion of Hg exceedances than fish from the relatively unpolluted Eastern Pacific. The present findings are consistent with broader literature identifying mercury as the principal driver of health risks in apex predators such as tuna, while Pb and Cd, although typically present at lower concentrations, remain important due to their cumulative toxicity (Hasan et al., 2023; Petroczi and Naughton, 2009).

Effect of processing, handling, and storage

Our findings indicate that heavy metal concentrations differed between fresh and frozen yellowfin tuna, with frozen products generally showing elevated levels. This pattern suggests that post-harvest processing and storage can influence contamination. Frozen food packaging has previously been identified as a potential source of heavy metals during preservation (Sood and Sharma, 2019), while cooking methods such as boiling, grilling, and frying may further increase concentrations through leaching from cookware (Abd-Elghany et al., 2020). Variability among samples also likely reflects differences in fishing grounds and post-catch handling, with consistently higher levels of Pb, Cd, and Hg in loins, fillets, and frozen products pointing to the cumulative effect of processing and storage conditions.

The higher concentrations observed in frozen products in this study align with previous reports where storage and preservation enhanced accumulation in muscle tissue (Storelli et al., 2020). Differences between fresh and processed products have also been noted in Italy, emphasizing the influence of supply chain conditions and post-harvest treatments (Miedico et al., 2020). Taken together, these patterns highlight that heavy metal levels in tuna are not only determined by the fishing ground but also by the handling chain after harvest. The finding that frozen products consistently contained higher concentrations than fresh samples is of particular concern, as frozen tuna represents a major commodity in both domestic and export markets. This underscores the need for stricter monitoring of post-harvest practices, especially storage conditions, to minimize contamination risks along the supply chain (Table 2).

Heavy metals as the main driver of health risk and vulnerable groups

Heavy metals are defined as potentially toxic metallic elements with a density higher than water, which can pose health risks when ingested at certain levels (Moukadiri et al., 2024; Zhang et al., 2024). Environmental contamination by heavy metals has widespread impacts, threatening the health of hundreds of millions of people worldwide (Okereafor et al., 2020). This threat becomes even more alarming when heavy metals enter the food chain, posing serious risks to both human and animal health (Kumar et al., 2023). In this context, numerous studies have investigated the relationship between heavy metal exposure and human health risks. For instance, the World Health Organization (WHO) has set a maximum limit for total chromium at 0.05 mg/L. However, the health risk interpretation of this threshold remains scientifically debated, primarily due to the limitations of analytical methods that cannot yet accurately distinguish between chromium species (World Health Organization, 2020). Therefore, to assess health risks more comprehensively, the EDI parameter is used. This method integrates data on heavy metal contaminant concentrations with the seafood consumption patterns of the studied population.

Although most EDI values fell within acceptable safety thresholds, women with high seafood consumption exceeded the limit of 100 for Pb and Hg, raising potential concerns. This indicates that while yellowfin tuna is generally safe for children and women under typical consumption levels, mercury accumulation poses a significant risk for high-consumption groups. The European Food Safety Authority (EFSA) recommends a maximum weekly fish intake of 750 g, adjusted by age and contaminant levels (Lozano-Bilbao et al., 2023), emphasizing the need for consumption guidelines tailored to vulnerable populations. These findings align with the ecological role of tuna as apex predators, which are particularly prone to biomagnification. Mercury, in particular, binds strongly to muscle proteins and is not easily eliminated (Petroczi and Naughton, 2009), making it the dominant driver of health risks in this study. While Pb and Cd contributed less to the overall risk, their cumulative toxic effects remain important, highlighting the necessity of long-term monitoring and management (Hasan et al., 2023).

The health risks posed by heavy metals are particularly severe for vulnerable groups such as children in their growth phase and pregnant women. This is because heavy metals can induce cancer through various molecular mechanisms (Coradduzza et al., 2024; Sharafi et al., 2022). Their carcinogenic risk is primarily correlated with their ability to generate reactive oxygen species (ROS)

Table 2. Heavy metal contamination and health risk profiles of seafood in different regions

Region / Study	Species/Product	Metals reported	Concentrations (mg/kg, wet weight unless stated)	Exceedance vs. limits	Risk metrics	References
Benoa Bay, Bali (Indonesia)	Yellowfin tuna (fresh & frozen)	Pb, Cd, Hg	Range: Pb 0.0002–0.1233; Cd 0.0001–0.0257; Hg 0.0010–0.9821 (varied by year & product type)	All mean concentrations within SNI & EU limits; Hg highest contributor to total risk	THQ <1 for most groups; TTHQ >1 for women (high-consumption) in certain years	This study
Indian Ocean, Sri Lanka	Yellowfin tuna (muscle) & swordfish	Hg, Cd	YFT: Hg <0.07–1.60; Cd <0.006–0.134. SF: Hg <0.07–4.30; Cd 0.006–0.180	Hg >1 mg/kg: 9.2% (YFT), 13.3% (SF); Cd >0.1 mg/kg: 3.1% (YFT)	EDI/THQ/HI assessed; safe at typical intake but vigilance advised	(Jinadasa et al., 2019)
Eastern Pacific (Ecuador)	Tuna products (canned, pre-cooked loins, some raw; skipjack, YFT, bigeye)	Hg, Cd, Pb	Mean (2009–2016, n=2572): Hg 0.24 ± 0.14, Cd 0.03 ± 0.03, Pb 0.05 ± 0.05. Retail canned: Hg 0.043 ± 0.004, Cd 0.012 ± 0.002, Pb <0.01	~0.58% near/just over limits (mostly Cd); all means < EU limits (Hg 1.0; Cd 0.1; Pb 0.3)	Safe for consumption under standards	(Ormaza-González et al., 2020)
Italy	Tuna fresh vs. canned	Hg, Cd, Pb	Mean Hg: fresh 0.517, canned 0.207; one canned sample Cd 0.22	11% of fresh tuna > Hg limit; 1 canned Cd non-compliant (0.22 mg/kg)	Higher Hg risk in fresh vs. canned; monitoring recommended	(Miedico et al., 2020)
Canary Islands (Atlantic)	Five tuna spp. (incl. YFT, bigeye, bluefin)	Cd, Pb (plus others)	T. thynnus (bluefin): Cd 0.280 ± 0.188; Fe and others elevated; species comparison in Table 2	T. thynnus: 75% exceeded Cd limit; 40% exceeded Pb limit; T. albacares (YFT) lower Cd & Pb	Chronic daily dose generally low; surveillance urged for T. thynnus	(Lozano-Bilbao et al., 2023)
Indonesia (Indian & Pacific)	Fresh YFT & swordfish landed in Indonesia	Cd, Pb, Hg	YFT Cd: Pacific 0.036 vs Indian 0.020 ($p<0.05$); Pb & Hg slightly higher in Pacific but NS; all metals within SNI & EU limits	PTWI for Pb in YFT (Indian Ocean scenario) 0.0038 mg/kg; others below PTWI	THQ/TTHQ < 1 across age groups; safe	(Oktariani et al., 2023)
Pattani Bay, Thailand	14 seafood species (fish, mollusks, crustaceans)	9 metals incl. Cd, Pb, Hg	Species-specific; all supported low risk at assessed intakes	THQ range: 7.79×10^{-8}–8.97×10^{-3}; HI: 4.30×10^{-5}–1.55×10^{2} (all <1)	No non-carcinogenic or carcinogenic risk	(Tanhan et al., 2022)

(Parida and Patel, 2023). ROS subsequently trigger DNA damage, genomic instability, oxidative stress, and mutations that lead to cancer initiation (Alfadul et al., 2023). Furthermore, heavy metals also damage DNA by disrupting its repair processes. These metals can bind to and inactivate critical cellular targets, such as the tumor suppressor protein p53 and enzymes involved in apoptosis and cell cycle integrity (Kocadal et al., 2020).

Public health and management implications

From a risk management perspective, this study provides critical input for developing targeted seafood consumption guidelines, particularly for vulnerable populations such as women of childbearing age and children. Effectively assessing the potential health implications of dietary heavy metal exposure from seafood requires the application of a standardized risk assessment index. However, average heavy metal concentrations in Benoa Bay yellowfin tuna fall within safe limits; elevated TTHQ values under high-consumption scenarios indicate potential concern. These data offer an essential metric for evaluating the potential non-carcinogenic and carcinogenic risks posed by toxic heavy metals (Hossain et al., 2023). This mirrors findings from other regional studies, where specific consumer groups face heightened risks despite generally safe averages (Zheng et al., 2007).

TTHQ values exceeding 1 in high-consumption groups underscore the need for more specific recommendations to prevent long-term health impacts. Practical strategies include diversifying marine protein sources, moderating consumption frequency and portion sizes for at-risk populations, and strengthening monitoring of heavy metals in fishery products. Similar patterns of elevated THQ/TTHQ, largely driven by mercury, have been reported across Southeast Asia (Gu et al., 2018; Tanhan et al., 2022), reinforcing the importance of proactive management.

Despite heavy metal concentrations remaining below maximum allowable levels, the findings are significant for documenting the current state of contamination in tuna products. This baseline data will facilitate future monitoring of trends in fishery commodities, potentially providing early indicators of environmental degradation and its consequences for food security. At the same time, management recommendations must be balanced with the reality that tuna is not only a cultural food preference but also a cornerstone of food security and livelihoods in coastal communities. In regions such as Bali, tuna represents both a critical source of affordable protein and a commodity sustaining local fishers through domestic and export markets. Overly restrictive consumption advisories could therefore generate unintended consequences, particularly for communities with limited access to alternative protein sources.

This tension highlights the need for context-sensitive approaches that safeguard public health without undermining food security. Dual strategies are recommended: (1) continuous surveillance of heavy metals in seafood to detect emerging risks early, and (2) public education that empowers consumers to make informed dietary choices. While international standards, such as the European Food Safety Authority's (EFSA) intake limits (Lozano-Bilbao et al., 2023), provide valuable benchmarks, localized guidelines are necessary to reflect regional dietary habits, contaminant levels, and the socioeconomic reliance on tuna. By integrating food safety with food security considerations, policymakers can develop adaptive advisories that protect vulnerable populations while sustaining the vital role of tuna in coastal diets and economies. Given Benoa Harbour's ongoing rapid industrialization and associated rise in pollution, this data is indispensable for implementing proactive risk mitigation, formulating sound regulations, and safeguarding consumer health through the long-term security of seafood.

CONCLUSIONS

This study demonstrated that concentrations of Pb, Cd, and Hg in fresh and frozen yellowfin tuna from Benoa Bay generally remained within internationally accepted safety limits, with most target hazard quotient (THQ) and total target hazard quotient (TTHQ) values suggesting low non-carcinogenic risks for the average consumer. However, under high-consumption scenarios, particularly among women of childbearing age, THQ and TTHQ values occasionally exceeded the safety threshold, driven largely by Hg exposure. These results underline the importance of accounting for consumption frequency and demographic sensitivity in risk assessments, since seafood safety cannot be fully evaluated on mean concentrations alone but must also reflect real dietary practices.

An important insight from this study is the difference between fresh and frozen samples, with frozen tuna showing higher heavy metal concentrations. This pattern suggests that contamination risks are not solely ecological but may also be influenced by post-harvest handling, storage, and supply chain processes. Such findings point to the need for food safety assessments that move beyond field-based monitoring to include evaluation of preservation and processing methods, as these may amplify or mitigate consumer risks. Integrating environmental monitoring with seafood value chain analysis can therefore provide a more comprehensive understanding of how heavy metals enter and persist in food systems. Although heavy metal levels in Benoa Bay tuna were lower or comparable to those reported in several other global hotspots, their presence in a highly traded and widely consumed commodity such as tuna raises broader implications for public health and fisheries-dependent economies. Beyond ecological factors, the potential contribution of controlled sources linked to urbanization and industrialization, such as wastewater discharge, port and tourism activities, and industrial runoff, must also be considered as ongoing drivers of contamination. Proactive risk communication and dietary guidance tailored to sensitive populations, combined with continuous monitoring, can reduce consumer exposure while maintaining confidence in seafood markets. Ultimately, ensuring seafood safety requires a governance approach that integrates fisheries management, food safety regulation, pollution control, and sustainable trade practices, aligning local actions with international frameworks such as the sustainable development goals (SDG) 14.

Aknowledgements

The authors would like to express their deepest gratitude to all staff who assisted during the field sampling and laboratory analyses. Special thanks are extended to the Research Group of Biological Health, Study Program of Biology, Faculty of Health and Science, Universitas Dhyana Pura, and PT. Intimas Surya, Benoa Port, for providing essential laboratory facilities and technical support. The authors also thank all the fishermen and tuna fish farmers who provided assistance during the research. Thanks to Ahmad Ilham Rabanni Erawan from the Indo Ocean Foundation for facilitating the creation of this research map.

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