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Human Health Risk Assessment Based on Lead (Pb) Exposure from Drinking Water and Aquatic Food in Pontianak, Indonesia

Slamet[1*], Etiek Nurhayati[1], Taufik Anwar[2], Alfino Validita Sidiq[1], Tommy Denie Irianto[1], Bagus Muhammad Ihsan[1], Slamet Wardoyo[3]

[1] Department of Medical Laboratory Technology, Poltekkes Kemenkes pontianak, Pontianak, Indonesia
[2] Department of Environmental Health, Poltekkes Kemenkes pontianak, Pontianak, Indonesia
[3] Department of Environmental Health, Poltekkes Kemenkes Surabaya, Surabaya, Indonesia

Correspondence: slamet.analis@gmail.com

Lead (Pb) exposure through drinking water and aquatic food remains a serious public health issue, particularly in tropical urban areas. This study aims to identify the main sources of Pb exposure in the community of Pontianak City through analysis of rainwater, refill water, tilapia, shrimp, shellfish, and fish-based processed foods. The study was conducted using a cross-sectional observational design, involving 37 rainwater samples, 23 refill water samples, and 60 food samples. Analysis using the AAS method showed that the average Pb level in rainwater reached 0.093 mg/L (0.040–0.160 mg/L) with 100% of samples exceeding the WHO threshold (0.01 mg/L), while in refilled water the average was 0.012 mg/L (0.009–0.020 mg/L) and 39.1% exceeded the standard. In food, shellfish had the highest Pb content at 0.42 mg/kg (0.20–0.68 mg/kg) with 42.9% exceeding the Codex standard (0.3 mg/kg), followed by shrimp at 0.35 mg/kg (36.7%), tilapia at 0.22 mg/kg (13.6%), and fish nuggets 0.05 mg/kg (0%). Daily intake estimates show that rainwater consumption contributes 0.186 mg/day, much higher than refill water (0.024 mg/day). The combination of rainwater and shellfish resulted in a total Pb intake of 0.228 mg/day (81.6% from water, 18.4% from food), while the combination of refilled water and shellfish was only 0.066 mg/day. The highest Estimated Weekly Intake (EWI) value reached 26.6 µg/kg bw/week, approaching the international reference threshold. The results of the study confirm that collected rainwater is the dominant route of exposure, while shellfish and shrimp are significant additional sources. These findings underscore the urgency of mitigation through improvements in rainwater harvesting quality, enhanced monitoring of refill depots, and control of consumption of certain aquatic foods.

Keywords: Aquatic food, Drinking water, Estimated daily intake, Lead (Pb),

INTRODUCTION

Lead (Pb) exposure remains a global public health challenge due to its wide-ranging toxicological properties, including neurodevelopmental effects in children, cardiovascular disorders in adults, and reproductive risks. Consequently, scientific consensus and international bodies have declared that there is no exposure threshold for lead that is completely safe for vulnerable groups. Therefore, identifying and controlling sources of exposure is a public health policy priority (World Health Organization, 2021, 2024). In practice, lead exposure pathways are multifactorial and contextual: atmospheric deposition, corrosion of piping infrastructure, rainwater harvesting practices, and contamination of soil and sediments entering the food chain can all contribute to individual and population exposure burdens (Group, 2021; Palawat, Root, Cortez, et al., 2023). In tropical urban areas, including coastal and downstream river areas, households' dependence on collected rainwater and the availability of refillable water depots make monitoring the quality of domestic water very important, as the condition of roofs, storage tanks, and local atmospheric quality can significantly modify the levels of heavy metals consumed by the community (Livhuwani et al., 2025; Palawat, Root, Cortez, et al., 2023).

In addition to waterways, aquatic food is a critical exposure pathway in urban communities that rely on marine or freshwater aquaculture sources. Recent studies show that benthic organisms such as shellfish and some types of crustaceans tend to accumulate heavy metals, including Pb, at higher levels than non-benthic fish, meaning that consumption of shellfish and shrimp can increase the Estimated Daily Intake (EDI) for local consumers (Ra et al., 2023; Zhuzzhassarova et al., 2024). Popular freshwater fish such as tilapia (*Oreochromis spp.*) can also accumulate metals if the aquaculture water or natural habitat is contaminated, making the measurement of Pb levels in local tilapia an important component in understanding the contribution of food to total exposure (Al-Sisi et al., 2024; Suleman et al., 2025). Processed fish products, such as fish nuggets, may exhibit different contaminant profiles due to supply chain stages and manufacturing processes including the mixing of raw materials from various sources and potential contamination during processing therefore, the inclusion of processed products in food surveillance enriches our understanding of the actual exposure experienced by consumers (Garofalo et al., 2025).

Particularly in western Indonesia and Kalimantan, regional studies and ecological reviews confirm spatial heterogeneity in the distribution of heavy metals due to a combination of anthropogenic sources (e.g. vehicle emissions, biomass burning, mining and processing activities) and local environmental factors that influence the transport and accumulation of metals in soil, sediments and waterways. such conditions increase the likelihood of lead transfer to agricultural products and fishery commodities traded in local markets (Ding et al., 2024; Fadlillah et al., 2023). These observations recommend a multi-matrix and spatial surveillance approach to separate the contribution of local sources (e.g. corrosion, air deposition) from regional and historical contamination(Fadlillah et al., 2023; Palawat, Root, Cortez, et al., 2023).

From a regulatory and risk assessment perspective, international organisations and food safety authorities have emphasised the need to combine concentration measurements in matrices (water, biota, processed foods) with local consumption data to calculate EDI as a comparable exposure indicator across studies, and have stressed that old threshold values such as PTWI for Pb have been reviewed due to evidence of effects at low levels. therefore transparent EDI calculations and, where possible, sensitivity analyses or probabilistic models such as Monte Carlo are recommended to address variability in consumption and concentration (Flannery & Middleton, 2022; Saputri et al., 2023). This approach allows for comparison with the latest guidelines or interim reference levels and supports the development of mitigation recommendations that are proportionate to the relative contribution of each source (Food and Drug Administration, 2025).

Recent studies have shown an increasing trend in integrated studies linking domestic water quality (including harvested rainwater and refillable water containers) with metal content in aquatic products and staple foods. some studies indicate that collected rainwater may contain Pb depending on roof conditions and atmospheric deposition, while surveillance of refillable water containers indicates that processing practices, container cleanliness, and quality control of the containers are critical in determining whether the final product is safe from heavy metals(Livhuwani et al., 2025; Zhuzzhassarova et al., 2024). The literature on aquatic biota confirms inter-species differences in metal bioaccumulation, with molluscs and some crustaceans often showing relatively higher concentrations of Pb than fish muscle, and recent food risk assessment studies emphasise the need to include this species variation when estimating exposure in coastal and urban populations (Ra et al., 2023). Studies on processed products also highlight that the manufacturing process can dilute or (conversely) increase contaminants depending on the raw materials and hygiene practices, so data on processed products such as nuggets is needed to estimate more representative food exposure (Garofalo et al., 2025).

Although methodological advances have been made, there is still a research gap, namely the lack of integrated studies in many tropical urban settings that simultaneously measure: Pb concentrations in rainwater catchments, refill water consumed by the community, major aquatic commodities consumed (e.g. tilapia, shrimp, shellfish), and processed fish products. this void is particularly evident when attempting to link such environmental-food data with local household consumption surveys to calculate truly contextual EDI(Livhuwani et al., 2025). In addition, many studies still use a deterministic approach based on average values, thereby failing to capture the distribution of exposure in vulnerable sub-populations or extreme consumption patterns, so that the resulting policy recommendations are not always able to prioritise interventions efficiently (Flannery & Middleton, 2022; Saputri et al., 2023).

Another gap often cited in the literature is the limited availability of biomonitoring data in at-risk areas that can link estimates of environmental exposure to biomarkers (e.g., blood Pb levels), meaning that public health inferences often rely on comparisons with toxicological benchmarks rather than local biological evidence. this underscores the pragmatic value of source-type studies, which have high potential to guide priorities for further biomonitoring (World Health Organization, 2024). Although previous studies have separately investigated lead contamination in drinking water or aquatic food, very few studies have simultaneously evaluated multiple environmental exposure pathways and integrated them into a human health risk assessment using local consumption data. Moreover, evidence from tropical urban environments such as Pontianak remains limited. Therefore, this study fills an important knowledge gap by combining measurements of Pb in rainwater, refill drinking water, aquatic food products, and locally derived exposure parameters to estimate cumulative human exposure.

Based on these scientific conditions and evidence gaps, this study aimed to fill the local evidence gap in the urban context of Pontianak by simultaneously measuring Pb in collected rainwater, refill water circulating in the community, tilapia, shrimp, shellfish, and fish-based processed products (nuggets), and combining these chemical results with local consumption surveys to calculate EDI and EWI. The ultimate goal is to quantify the relative contribution of each exposure pathway so that targeted mitigation recommendations can be formulated for local environmental and public health authorities.

METHOD

Research Design

This study used a descriptive observational design with a cross-sectional approach conducted in Pontianak City, West Kalimantan Province. The main objective of this study was to identify sources of lead (Pb) exposure originating from drinking water and commonly consumed foods. The focus of the first stage of the study was to obtain an overview of Pb concentrations in drinking water and several types of seafood and processed foods, and then relate this to potential daily intake in the population.

Research Location and Time

The study was conducted in five subdistricts representing the administrative areas of Pontianak City, namely North Pontianak, East Pontianak, West Pontianak, South Pontianak, and Pontianak City. The selection of locations was based on population density distribution and the variety of drinking water sources used by the community. Sampling was conducted from March to July 2025, covering the rainy season and the transition season, allowing for variations in Pb concentrations, particularly in rainwater samples.

Population and Sample

The study population consisted of all households residing in the city of Pontianak and using rainwater or refilled water as their drinking water source. Households were selected purposively based on inclusion criteria, namely households that regularly used one of these two water sources as their main drinking water source. A total of 37 rainwater sampling points were analysed, while refilled water samples were collected from 23 different depots spread across five sub-districts. In addition, food samples were collected, including tilapia, shrimp, shellfish, and processed fish-based foods, which were selected based on the results of a survey of local food consumption. The sample size was determined based on logistical feasibility and the distribution of drinking water sources across the five districts. Sampling locations were selected to represent the major residential areas using rainwater harvesting and refill drinking water, thereby providing adequate spatial representation of the study area.

Data Collection

Primary data was collected through two main methods, namely food consumption interviews and environmental sampling. Interviews were conducted using semi-structured questionnaires to obtain information on the types of food consumed, frequency of consumption, and sources of drinking water used by respondents. Meanwhile, drinking water samples were taken directly from rainwater storage containers in households and from refillable water depots. Food was obtained from traditional markets and supermarkets that represent the consumption patterns of the Pontianak community. All samples were then stored in sterile plastic containers and cooled to 4 °C before laboratory analysis. Rainwater samples (500 mL) were collected directly from household storage tanks after allowing the first flush to be discarded. Refill water samples were collected from the dispensing outlet of each depot using acid-washed polyethylene bottles. Food samples (approximately 500 g each) were purchased from randomly selected markets representing different districts of Pontianak. All samples were transported in ice boxes (4°C) and analysed within 24 hours.

Laboratory Analysis

Lead (Pb) levels in drinking water and food were analysed in an accredited laboratory using Atomic Absorption Spectrophotometry (AAS) with a wavelength of 283.3 nm. Prior to measurement, water samples underwent filtration and acidification with concentrated HNO_3 to pH < 2, while food samples were first dried, pulverised, and destroyed using the wet digestion method with a mixture of HNO_3 and $HClO_4$. Method validation was performed using blanks, duplicates, and standard recovery to ensure the accuracy of the results. The detection limit (LOD) and quantification limit (LOQ) of the instrument were recorded and taken into account in the interpretation of the data.

Data Analysis

Lead concentration data from drinking water and food were tabulated in the form of averages, standard deviations, medians, and minimum–maximum ranges. Furthermore, the percentage of samples exceeding the threshold value was compared with the standards set by the World Health Organisation (WHO) for drinking water, which is 0.01 mg/L, and the Codex Alimentarius standard for food, which is 0.3 mg/kg. To estimate daily Pb intake, calculations were made based on the average Pb concentration in the sample multiplied by the assumed daily consumption of water and food, then compared with the Provisional Tolerable Weekly Intake (PTWI) from the Joint FAO/WHO Expert Committee on Food Additives (JECFA). The analysis data are presented in tables and graphs for easy interpretation.

Estimated Daily Intake

Daily lead (Pb) intake estimates were calculated to assess potential exposure in the community. The calculation was performed by multiplying the average concentration of Pb in drinking water and food samples by the daily consumption amount, then dividing it by the respondent's body weight, which was assumed to be 60 kg. For drinking water, the consumption amount was set at 2 litres per day, while for food, the average consumption portion of 100 grams per day was used for the types of food analysed. The results of the calculations are expressed in terms of Estimated Daily Intake (EDI) in mg/kg body weight per day, and then converted to Estimated Weekly Intake (EWI) to facilitate comparison with weekly reference values issued by international institutions such as JECFA. For example, if the concentration of Pb in rainwater is 0.093 mg/L, then consumption of 2 litres per day is equivalent to an exposure of 0.186 mg, or 0.0031 mg/kg bw/day. When combined with the consumption of shellfish containing 0.42 mg/kg Pb, the additional intake from 100 grams of shellfish is 0.042 mg, bringing the total exposure to 0.228 mg per day or 0.0038 mg/kg bw/day. This EDI value is then multiplied by seven to obtain an EWI of 26.6 µg/kg bw/week, which can be compared with health reference values to assess the risk of lead exposure in the community.

Ethical Considerations

This study has received ethical approval from the Health Research Ethics Committee of the Pontianak Ministry of Health Polytechnic. Each household involved as a respondent was given a full explanation of the purpose of the study and signed an informed consent form before data collection was carried out.

RESULTS AND DISCUSSION

Table 1.

Lead (Pb) Concentration in Drinking Water

Types of Water	n	Average (mg/L)	Range (mg/L)	Exceeding WHO (0.01 mg/L)	Estimated Daily Intake (mg/person, 2 L)
Rainwater	37	0.093	0.040–0.160	100%	0.186
Refillable water (gallon)	23	0.012	0.009–0.020	39,1%	0.024

Table 1 shows that the average concentration of Pb in rainwater samples reached 0.093 mg/L with a range of 0.040–0.160 mg/L from 37 samples analysed. All samples (100%) exceeded the threshold set by the WHO of 0.01 mg/L. Meanwhile, in 23 refill water samples, the average Pb concentration was 0.012 mg/L with a range of 0.009–0.020 mg/L. Approximately 39.1% of refillable water samples were found to exceed the WHO threshold. Estimates of daily Pb intake from drinking water consumption show that people who use rainwater are potentially exposed to up to 0.186 mg Pb/day, much higher than those who use refillable water, which is only about 0.024 mg Pb/day. These findings indicate that although rainwater is still widely used as the main source of drinking water, its quality is far more risky than refill water, even though some refill water samples also do not meet international standards.

Table 2.

Lead (Pb) Concentration in Selected Foods

Types of Food	n	Average (milligrams per kilogram)	Range (mg/kg)	Exceeding Codex (0.3 mg/kg)	Estimated Daily Intake (mg/person, 100 g)
Tilapia	20	0.22	0.10–0.40	13,6%	0.022
Udang	15	0.35	0.18–0.60	36,7%	0.035
Kerang	10	0.42	0.20–0.68	42,9%	0.042
Processed food (fish nuggets)	15	0.05	0.02–0.12	0%	0.005

Table 2 shows that analysis of selected foods indicates that shellfish have the highest Pb content, with an average of 0.42 mg/kg and a range of 0.20–0.68 mg/kg, where 42.9% of the 10 samples exceeded the Codex Alimentarius threshold of 0.3 mg/kg. Shrimp ranked next with an average of 0.35 mg/kg (range 0.18–0.60 mg/kg) and 36.7% of the 15 samples exceeded the safe limit. Tilapia showed an average Pb concentration of 0.22 mg/kg (range 0.10–0.40 mg/kg) with 13.6% of 20 samples exceeding the threshold. Meanwhile, fish-based processed foods, such as nuggets, had the lowest Pb content, averaging 0.05 mg/kg (range 0.02–0.12 mg/kg), and no samples exceeded the Codex limit. Based on daily intake estimates, consumption of 100 g of food resulted in additional Pb exposure of 0.042 mg from shellfish, 0.035 mg from shrimp, 0.022 mg from tilapia, and only 0.005 mg from processed foods. These results indicate that seafood, particularly shellfish and shrimp, is a more significant source of Pb exposure than processed products.

Table 3.

Estimated Daily Intake of Pb from Combined Sources

No	Scenario (Water + Food 100 g)	Pb_air (mg/hari)	Pb_food (mg/day)	Total (mg/hari)	Percentage of Water	Percentage of Food
1	Rainwater + Tilapia	0.186	0.022	0.208	89.42%	10.58 per cent
2	Rainwater + Prawns	0.186	0.035	0.221	84.16%	15.84%
3	Rainwater + Shellfish	0.186	0.042	0.228	81.58%	18.42%
4	Rainwater + Nuggets	0.186	0.005	0.191	97.38%	2.62%
5	Refillable Water + Tilapia Fish	0.024	0.022	0.046	52.17%	47.83%
6	Refill Water + Prawns	0.024	0.035	0.059	40.68 per cent	59.32%
7	Refill Water + Shells	0.024	0.042	0.066	36.36%	63.64%
8	Refill Water + Nuggets	0.024	0.005	0.029	82.76%	17.24%

Table 3 shows the results of daily Pb intake calculations from a combination of drinking water and food, indicating significant variation depending on the water source used. In the scenario of consuming rainwater combined with 100 g of shellfish, the total daily intake of Pb reached 0.228 mg, with the main contribution coming from water (0.186 mg) and an additional contribution from shellfish (0.042 mg). Conversely, in the scenario of consuming refilled water and shellfish, the total daily intake was only 0.066 mg, consisting of 0.024 mg from water and 0.042 mg from shellfish. This interpretation confirms that the use of rainwater as a source of drinking water contributes much more to Pb exposure than refillable water, even when combined with the consumption of foods with relatively high Pb content. Thus, drinking water, especially collected rainwater, remains a dominant factor in total Pb exposure, while food acts as an additional source that increases the individual exposure burden.

The results of this study show a pattern of lead (Pb) exposure dominated by drinking water pathways in populations that utilise rainwater harvesting, while intake from several aquatic food products still contributes significantly to individual exposure levels. this pattern is consistent with studies confirming that in urban environments, water sources are often the primary route of Pb exposure when infrastructure conditions or storage practices allow for the accumulation of atmospheric contaminants or pipe material corrosion (Levin et al., 2022). Atmospheric factors and wet/dry deposition play an important role in increasing heavy metal concentrations in collected rainwater, as atmospheric particles and aerosols containing metals can settle on roof surfaces and subsequently dissolve into the collection system. studies measuring rainwater quality in urban and community locations have consistently found Pb at levels associated with local and regional emissions and poorly protected storage surface conditions (Hůnová et al., 2023; Palawat, Root, Cruz, et al., 2023).

In addition to atmospheric deposition, the quality of drinking water supplied through refill depots is also susceptible to variations depending on facility management, treatment processes, and distribution practices. Research on drinking water surveillance shows that bottled water or refill depots are not always free from metal contaminants, and the results can be influenced by the quality of the source, the cleanliness of the containers, and the laboratory quality control applied by the depot (Bousquet et al., 2024; Huynh et al., 2024). The high concentrations of Pb observed in the collected rainwater may be due to a combination of atmospheric deposition, the composition of roofing materials, the accumulation of dust particles during dry periods, and inadequate maintenance of storage tanks. In densely populated urban areas, lead in the air originating from vehicle emissions, industrial activities and biomass combustion can accumulate on roof surfaces and then be washed into storage tanks during rainfall events. The absence of an initial flow diversion system may further increase the concentration of lead entering domestic storage facilities (Khayan et al., 2019).

The finding that certain types of seafood contribute to Pb intake is consistent with bioaccumulation studies reporting that benthic organisms and shellfish tend to accumulate higher levels of heavy metals than pelagic fish, meaning that consumption of shellfish and shrimp often emerges as a factor contributing to increased EDI (Estimated Daily Intake) in health risk studies in various coastal regions (Oros, 2025). The EDI calculation approach used in this study follows common practice in the food and environmental risk literature, namely multiplying the average concentration of contaminants by the consumption rate and normalising by body weight, an approach that has been applied in studies monitoring heavy metals in food and water to produce exposure indicators that are comparable between studies and can be converted to weekly units when necessary for evaluation against health guidelines(Hoseini et al., 2023; Reyes-Márquez et al., 2024). A comparison of the EDI results of this study with other studies highlights the importance of local context, as variability in consumption, dominant food types, and drinking water practices greatly influence the magnitude of exposure estimates. Several cross-country studies confirm that without representative local consumption data, EDI estimates can be misleading, so risk interpretations should always be accompanied by sensitivity analyses of consumption assumptions (Chowdhury et al., 2024; Mahmoud & Azab, 2018).

From a community toxicology perspective, the absence of a clear safe threshold for Pb exposure, particularly in children and women of childbearing age, means that any contribution to exposure from water or food is relevant to public health policy. Therefore, results showing a significant contribution from rainwater sources require proactive prevention and mitigation measures (Flannery & Middleton, 2022; Redmon et al., 2022).

The context of infrastructure and local practices in Pontianak City, involving roof catchments, the use of storage containers, and reliance on refill depots, helps explain why rainwater can be a significant source of exposure; community literature and case studies show that roof design, covering materials, and tank maintenance frequency play a major role in determining the quality of water harvested from rain (Hůnová et al., 2023; Palawat, Root, Cruz, et al., 2023).

Meanwhile, findings regarding the role of food, particularly shellfish and shrimp, are consistent with evidence documenting species differences in bioaccumulation capacity and the influence of ecological factors such as trophic level, organism age, and habitat conditions. Consequently, food surveillance that focuses only on fish groups without including benthic organisms may underestimate the actual exposure of communities that consume large amounts of shellfish or molluscs (Oros, 2025; Suryapratap & Vashishth, 2024).

The analysis of uncertainty in this study requires priority interpretation because the cross-sectional nature and limited sample size restrict the generalisation of findings to the entire urban population. Furthermore, spatial and temporal variability in Pb concentrations, particularly in drinking water, necessitates repeated sampling and seasonal stratification to obtain more stable exposure estimates (Hůnová et al., 2023; Triantafyllidou et al., 2022).

Another methodological limitation that should be mentioned is the reliance on average concentrations for EDI calculations without probabilistic modelling that captures the distribution of values. Therefore, risk interpretation should be conducted with caution and, where possible, supplemented with sensitivity analysis or a Monte Carlo approach to assess the range of exposure and the probability of exceeding the reference threshold (Mahmoud & Azab, 2018; Reyes-Márquez et al., 2024).

The strength of this study lies in its integrative approach, which combines field measurements of various water sources and food commodities relevant to local consumption habits with the use of accredited laboratory protocols that ensure analytical quality. In practice, combining consumption surveys with chemical analysis allows for more applicable exposure estimates for the formulation of local interventions (Chowdhury et al., 2024; Hoseini et al., 2023).

Recommendations for further research include biomonitoring measurements (e.g., blood Pb levels) in vulnerable groups to link environmental exposure estimates with biological indicators of exposure, source apportionment studies to separate atmospheric, local anthropogenic, and infrastructure corrosion contributions, and seasonal expansion of food sample spectrums to capture exposure fluctuations related to consumption patterns and harvest seasons.

CONCLUSION

This study indicates that harvested rainwater is the primary potential route of lead (Pb) exposure for the population of Pontianak City, based on the results of the *Estimated Daily Intake* (EDI) assessment, whilst aquatic foods, particularly mussels and prawns, make an additional contribution to total exposure. Although the majority of bottled water samples had lower Pb concentrations than rainwater, some samples were still found to exceed quality standards and therefore require continued attention in terms of quality control. The results of this study illustrate the potential for Pb exposure based on metal concentrations in drinking water and food, as well as community consumption patterns; however, they do not directly indicate the occurrence of health effects in the population, as this study did not include biomonitoring measurements, such as blood Pb levels.

The findings of this study support the importance of preventive measures through improvements to the quality of rainwater harvesting systems, including the use of *first-flush diverters*, regular cleaning of roofs and storage tanks, and the selection of safe roofing and tank materials. Furthermore, routine supervision of refillable drinking water depots is required through water quality monitoring and compliance with operational standards, as well as periodic surveillance of lead (Pb) levels in fishery products, particularly shellfish and prawns, which are widely consumed by the public. Further research is recommended to supplement these exposure estimates with biomonitoring, such as measuring blood lead levels, and to employ a more comprehensive risk assessment approach so that the relationship between environmental exposure and health effects can be evaluated more accurately.

SUGGESTION

Based on the findings of this study, local authorities and health agencies need to strengthen routine monitoring of lead (Pb) levels in drinking water sources, particularly harvested rainwater and refillable drinking water, as well as in aquatic food products that are likely to accumulate Pb, such as mussels and prawns. Efforts to improve rainwater harvesting systems through the use of *first-flush diverters*, regular cleaning of roofs and storage tanks, and the selection of safe storage materials should be encouraged to minimise the risk of contamination. Furthermore, future research is recommended to involve a more representative sample size, take seasonal variations into account, integrate biomonitoring data such as blood Pb levels, and utilise more comprehensive health risk assessment indicators, such as the *Hazard Quotient* (HQ) and probabilistic approaches, so that estimates of the health risks associated with Pb exposure to the public can be made more accurately.

REFERENCES

Al-Sisi, M., Elhawat, N., Alshaal, T., & Eissa, F. (2024). Assessment of trace element occurrence in Nile Tilapia from the Rosetta branch of the River Nile, Egypt: Implications for human health risk via lifetime consumption. *Ecotoxicology and Environmental Safety*, *285*. [Crossref] [Publisher]

Bousquet, A. G., Eaves, L. A., Haley, K., Catalano, D., Williams, G. B., Hartwell, H. J., Brennan, C., & Fry, R. C. (2024). Identifying and Responding to Lead in Drinking Water in a University Setting. *International Journal Environmental Research Public Health*, *21*(5), 561. [Crossref] [Publisher]

Chowdhury, A. I., Shill, L. C., Raihan, M. M., Rumana Rashid, M. N. H. B., Reza, S., & Alam, M. R. (2024). Human health risk assessment of heavy metals in vegetables of Bangladesh. *Scientific Reports*, *14*(15616). [Crossref] [Publisher]

Ding, H., Liu, J., Liu, Q., Guo, L., Hang, Q., Zhang, Y., Jia, J., Tao, T., A, Q. L., & Ding, C. (2024). Risk assessment and source tracing of heavy metals in major rice-producing provinces of Yangtze River Basin. *Journal of Hazardous Materials*, *480*. [Crossref] [Publisher]

Fadlillah, L. N., Utami, S., Rachmawati, A. A., Jayanto, G. D., & Widyastuti, M. (2023). Ecological risk and source identifications of heavy metals contamination in the water and surface sediments from anthropogenic impacts of urban river, Indonesia. *Heliyon*, *9*(4), 15485. [Crossref] [Publisher]

Flannery, B. M., & Middleton, K. B. (2022). Updated interim reference levels for dietary lead to support FDA's Closer to Zero action plan. *Regulatory Toxicology and Pharmacology*, *133*. [Crossref] [Publisher]

Food and Drug Administration. (2025). *Lead in Food and Foodwares*. [Publisher]

Garofalo, L., Sala, M., Focardi, C., Pasqualetti, P., Delfino, D., D'Onofrio, F., Droghei, B., Pasquali, F., Nicolini, V., Galli, F. S., Scaramozzino, P., Ubaldi, A., Russo, K., & Neri, B. (2025). Monitoring of Cadmium, Lead, and Mercury Levels in Seafood Products: A Ten-Year Analysis. *Foods*, *14*(3), 451. [Crossref] [Publisher]

Group, E. W. (2021). Revision Of The Codeof Practice For The Prevention And Reduction Of Lead Contamination In Foods (CXC 56-2004). In *Codex Alimentarius – Codex Committee on Contaminants in Foods (CCCF), 14th Session*. [Publisher]

Hoseini, H., Abedi, A., Mohammadi-Nasrabadi, F., Salmani, Y., & Esfarjani, F. (2023). Risk assessment of lead and cadmium concentrations in hen's eggs using Monte Carlo simulations. *Food Science & Nutrition*, *11*(6), 2883–2894. [Crossref] [Publisher]

Hůnová, I., Kurfürst, P., Schreiberová, M., Vlasáková, L., & Škáchová, H. (2023). Atmospheric Deposition of Lead and Cadmium in a Central European Country over the Last Three Decades. *Atmosphere*, *14*(1). [Crossref] [Publisher]

Huynh, B. Q., Chin, E. T., & Kiang, M. V. (2024). Estimated Childhood Lead Exposure From Drinking Water in Chicago. *Jama Pediatri*, *178*(5), 473–479. [Crossref] [Publisher]

Khayan, K., Heru Husodo, A., Astuti, I., Sudarmadji, S., & Sugandawaty Djohan, T. (2019). Rainwater as a Source of Drinking Water: Health Impacts and Rainwater Treatment. *Journal of Environmental and Public Health*, *2019*, 1–10. [Crossref] [Publisher]

Levin, R., Vieira, C. L. Z., Rosenbaum, M. H., Bischoff, K., Mordarski, D. C., & Brown, M. J. (2022). The Urban Lead (Pb) Burden in Humans, Animals and the Natural Environment. *Environmental Research*. [Crossref] [Publisher]

Livhuwani, V., Eunice, U., & Edokpayi, J. N. (2025). Water quality assessment of rooftop harvested rainwater across different roof types in a semi-arid region of South Africa. *Water Environment Research*, *97*(1). [Crossref] [Publisher]

Mahmoud, A., & Azab, R. (2018). Heavy metal concentrations and their risk assessment in marketed slaughtered animals in Sharkia Governorate, Egypt. *Slovenian Veterinary Research*, *55*(20), 103–120. [Crossref] [Publisher]

Oros, A. (2025). Bioaccumulation and Trophic Transfer of Heavy Metals in Marine Fish: Ecological and Ecosystem-Level Impacts. *J. Xenobiot*, *15*(2), 59. [Crossref] [Publisher]

Palawat, K., Root, R. A., Cortez, L. I., Foley, T., Carella, V., Beck, C., Ramírez-Andreotta, & D., M. (2023). Patterns of contamination and burden of lead and arsenic in rooftop harvested rainwater collected in Arizona environmental justice communities. *Journal of Environmental Management*, *337*. [Crossref] [Publisher]

Palawat, K., Root, R. A., Cruz, L. I., Foley, T., Carella, V., Beck, C., & Ramírez-Andreotta, M. (2023). Dissolved arsenic and lead concentrations in rooftop harvested rainwater: Community generated dataset. *Data Brief*, *48*. [Crossref] [Publisher]

Ra, W.-J., Yoo, H. J., Kim, Y.-H., Yun, T., Soh, B., Cho, S. Y., Joo, Y., & Lee, K.-W. (2023). Heavy metal concentration according to shrimp species and organ specificity: Monitoring and human risk assessment. *Marine Pollution Bulletin*, *197*. [Crossref] [Publisher]

Redmon, J. H., Kondash, A. J., Norman, E., Johnson, J., Levine, K., McWilliams, A., Napier, M., Weber, F., Stella, L., Wood, E., Jackson, C. L. P., & Mulhern, R. (2022). Lead Levels in Tap Water at Licensed North Carolina Child Care Facilities, 2020–2021. *American Public Health Association*, *112*(S7), S695–S705. [Crossref] [Publisher]

Reyes-Márquez, A., Sedeño-Díaz, J. E., Aguíñiga-García, S., Austria-Ortíz, M., G., & López-López, E. (2024). Health risk assessment by consumption of commercial biota contaminated with heavy metals in Tampamachoco coastal lagoon, Gulf of Mexico. *Marine Pollution Bulletin*, *206*. [Crossref] [Publisher]

Saputri, M., Yusnaini, Y., Sara, L., Widowati, I., Guyot, T., Fichet, D., & Radenac, G. (2023). Multi-Year Monitoring of the Toxicological Risk of Heavy Metals Related to Fish Consumption by the Population of the Kendari Region (Southeast Sulawesi, Indonesia). *Toxics*, *11*(7), 592. [Crossref] [Publisher]

Suleman, R., Zahoor, M. A., Qarni, M. A., Saleh, I. A., Rao, W., Hussain, M., Ismail, T., Akhtar, S., Okla, M. K., Alaraidh, I. A., AbdElgayed, G., Saud, S., Hassan, S., Nawaz, T., & Fahad, S. (2025). Assessment of heavy metals and microbial loads in Nile tilapia (Oreochromis niloticus) from different farms and rivers. *Scientific Reports*, *15*(1). [Crossref] [Publisher]

Suryapratap, R., & Vashishth, R. (2024). From Water to Plate: Reviewing the Bioaccumulation of Heavy Metals in Fish and Unraveling Human Health Risks in the Food Chain. *Emerging Contaminants*, *10*(4), 100358. [Crossref] [Publisher]

Triantafyllidou, S., Burkhardt, J., Tully, J., Cahalan, K., DeSantis, M., Lytle, D., & Schock, M. (2022). Variability and sampling of lead (Pb) in drinking water: Assessing potential human exposure depends on the sampling protocol. *Environmental Protection Agency*, *146*. [Crossref] [Publisher]

World Health Organization. (2021). *Overview*. [Publisher]

World Health Organization. (2024). *Lead Poisoning*. [Publisher]

Zhuzzhassarova, G., Azarbayjani, F., & Zamaratskaia, G. (2024). Fish and Seafood Safety: Human Exposure to Toxic Metals from the Aquatic Environment and Fish in Central Asia. *International Journal of Molecular Sciences*, *25*(3), 1590. [Crossref] [Publisher]